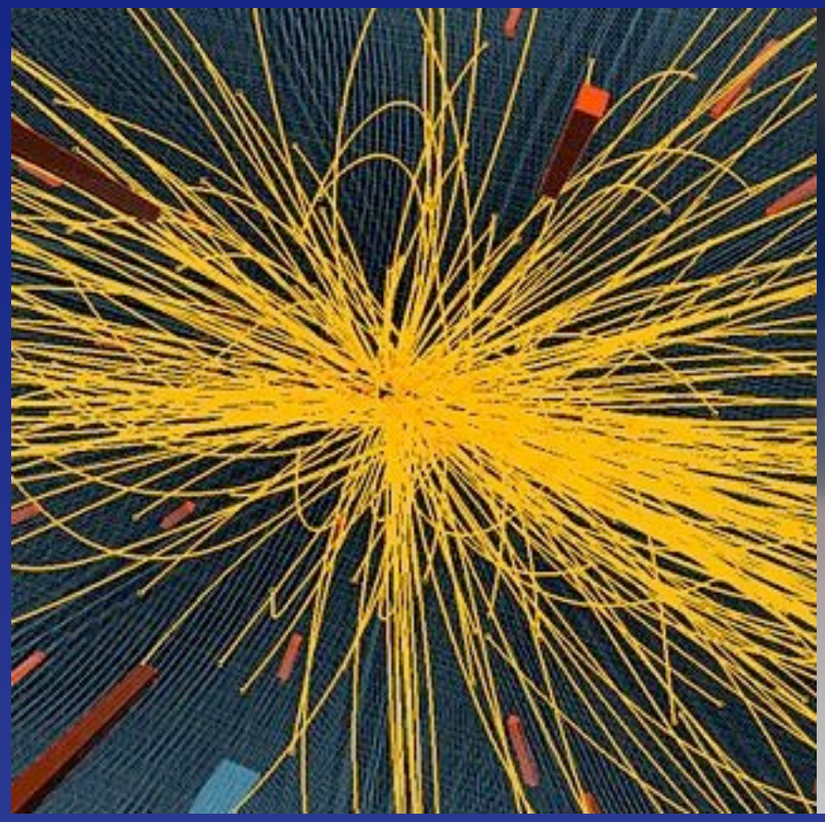
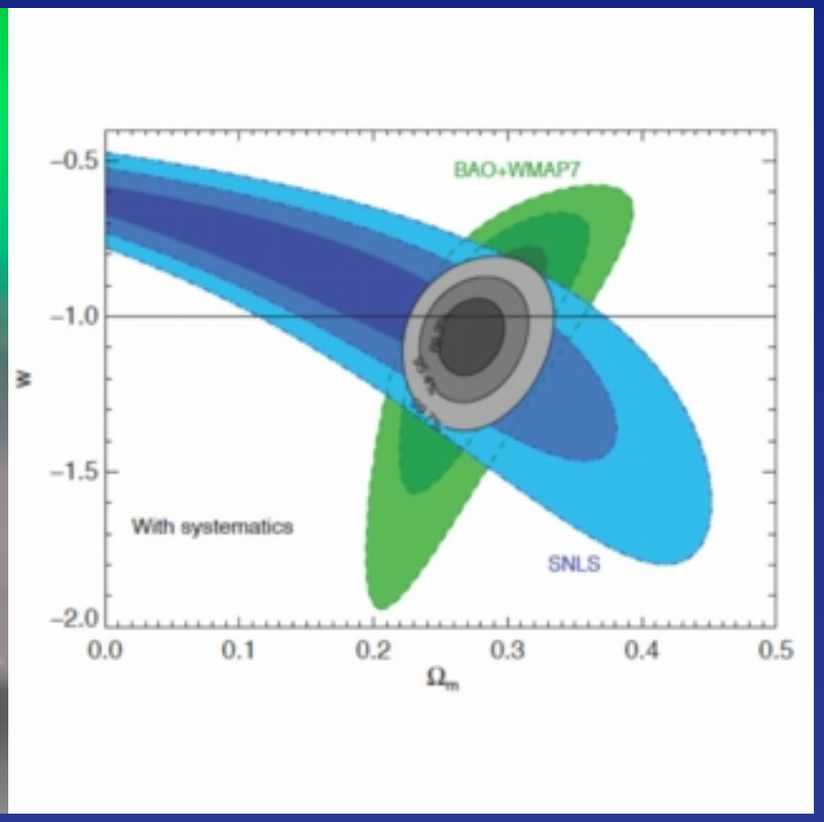
The Coming Revolutions in Particle Physics

Chris Quigg
Fermi National Accelerator Laboratory

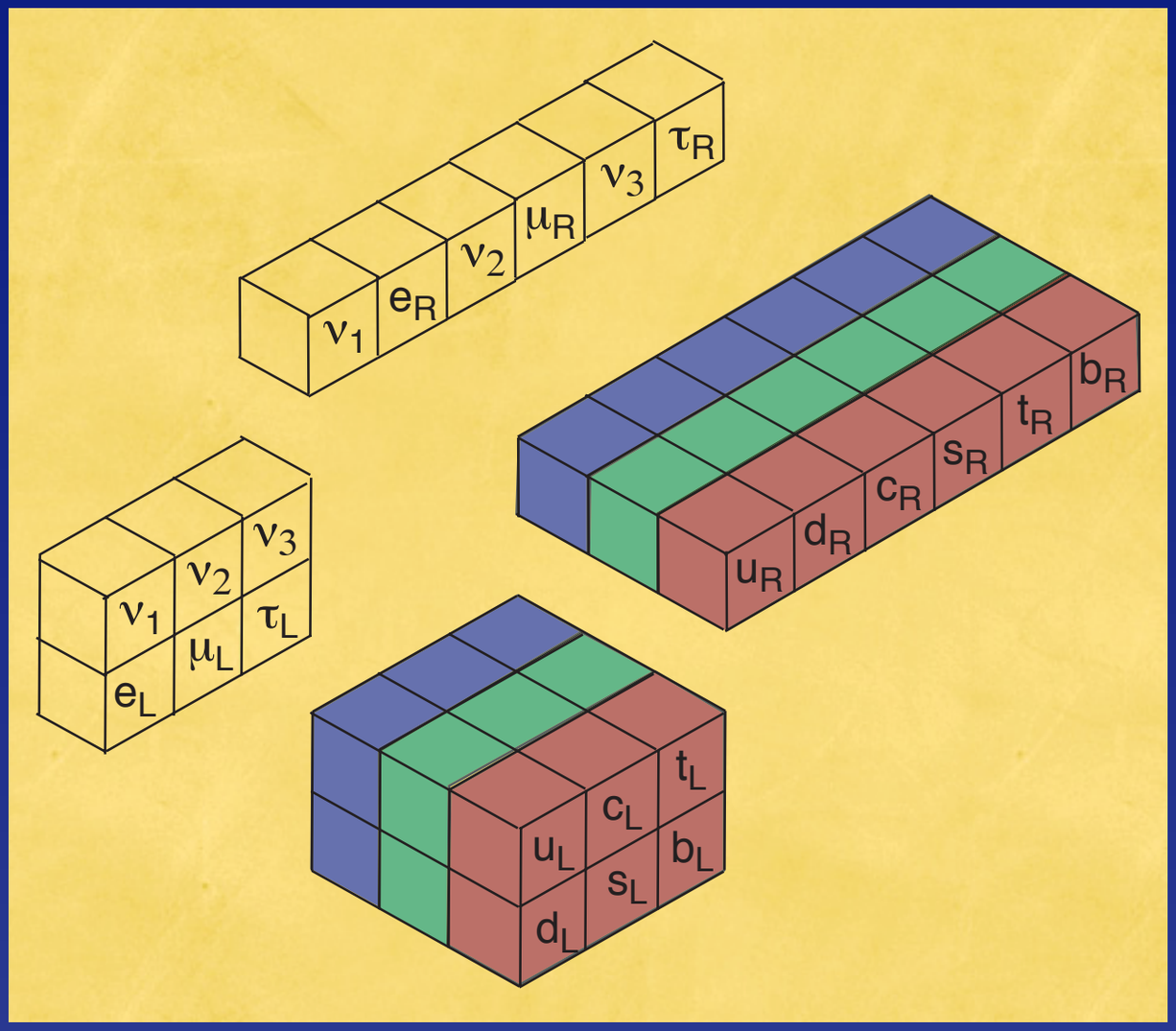




BNL Physics Colloquium · 5 April 2011

Two New Laws of Nature +

Pointlike ($r \leq 10^{-18}$ m) *quarks* and *leptons*

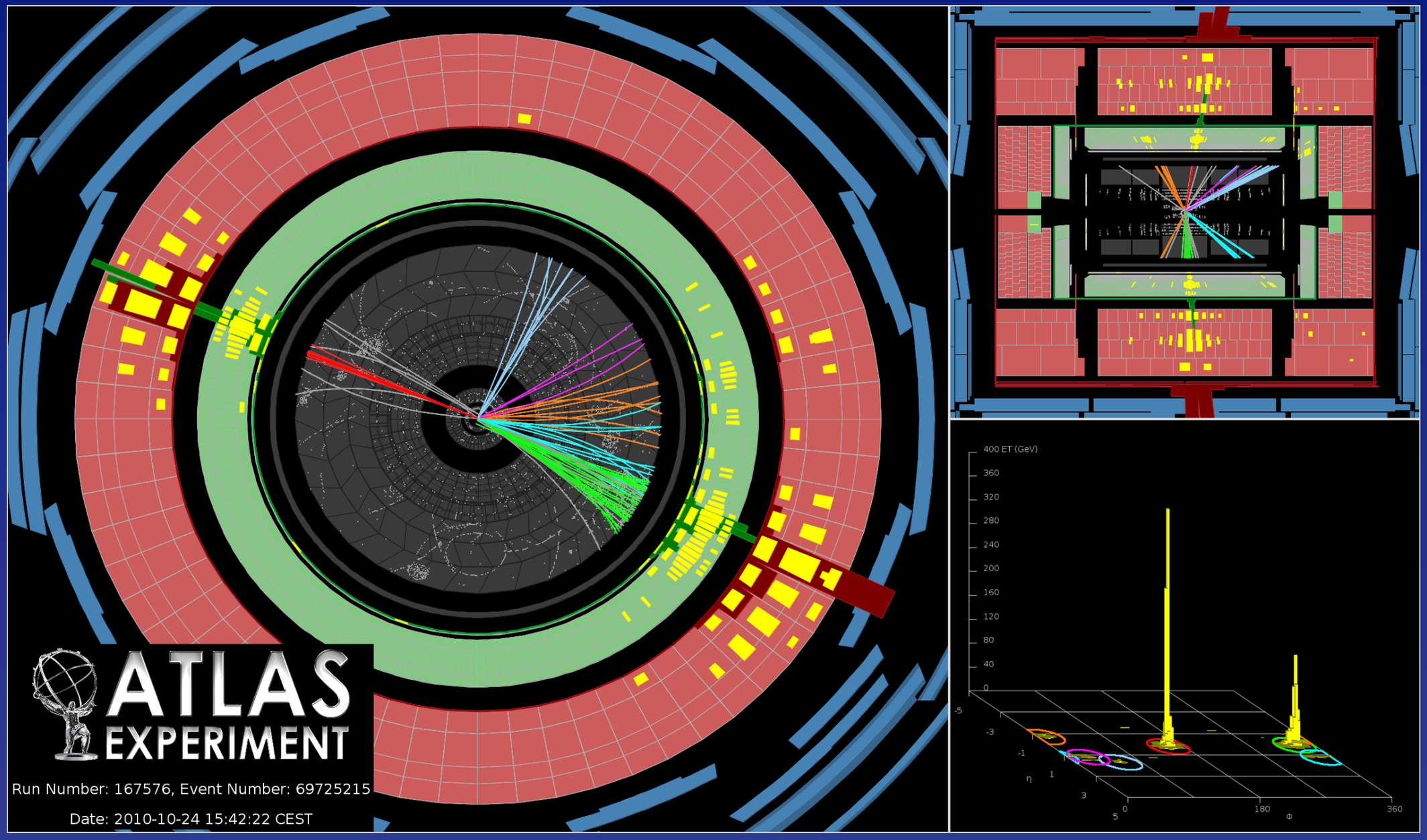


Interactions: $\mathsf{SU}(3)_\mathsf{c} \otimes \mathsf{SU}(2)_\mathsf{L} \otimes \mathsf{U}(1)_\mathsf{Y}$ gauge symmetries

Highly idealized

The World's Most Powerful Microscopes

nanonanophysics



Transverse momenta: 1.3 TeV + 1.2 TeV

Many tensions,
puzzles,
outstanding questions

Lots of new ideas

Beautiful experiments:
mature / new / dreams

Quantum Chromodynamics

Asymptotically free theory

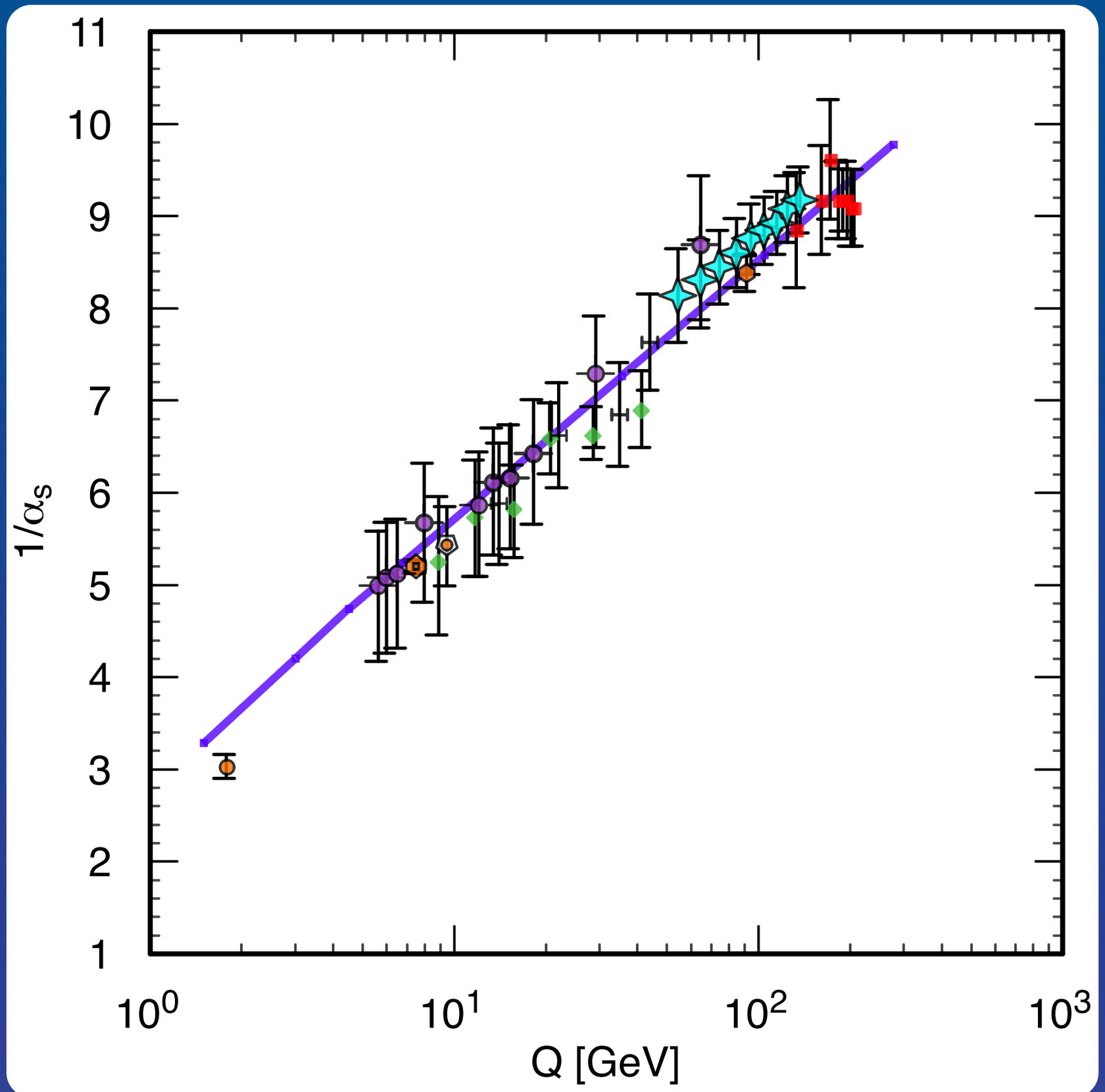
Many successes in perturbation theory to 1 TeV

Growing understanding: nonperturbative regime

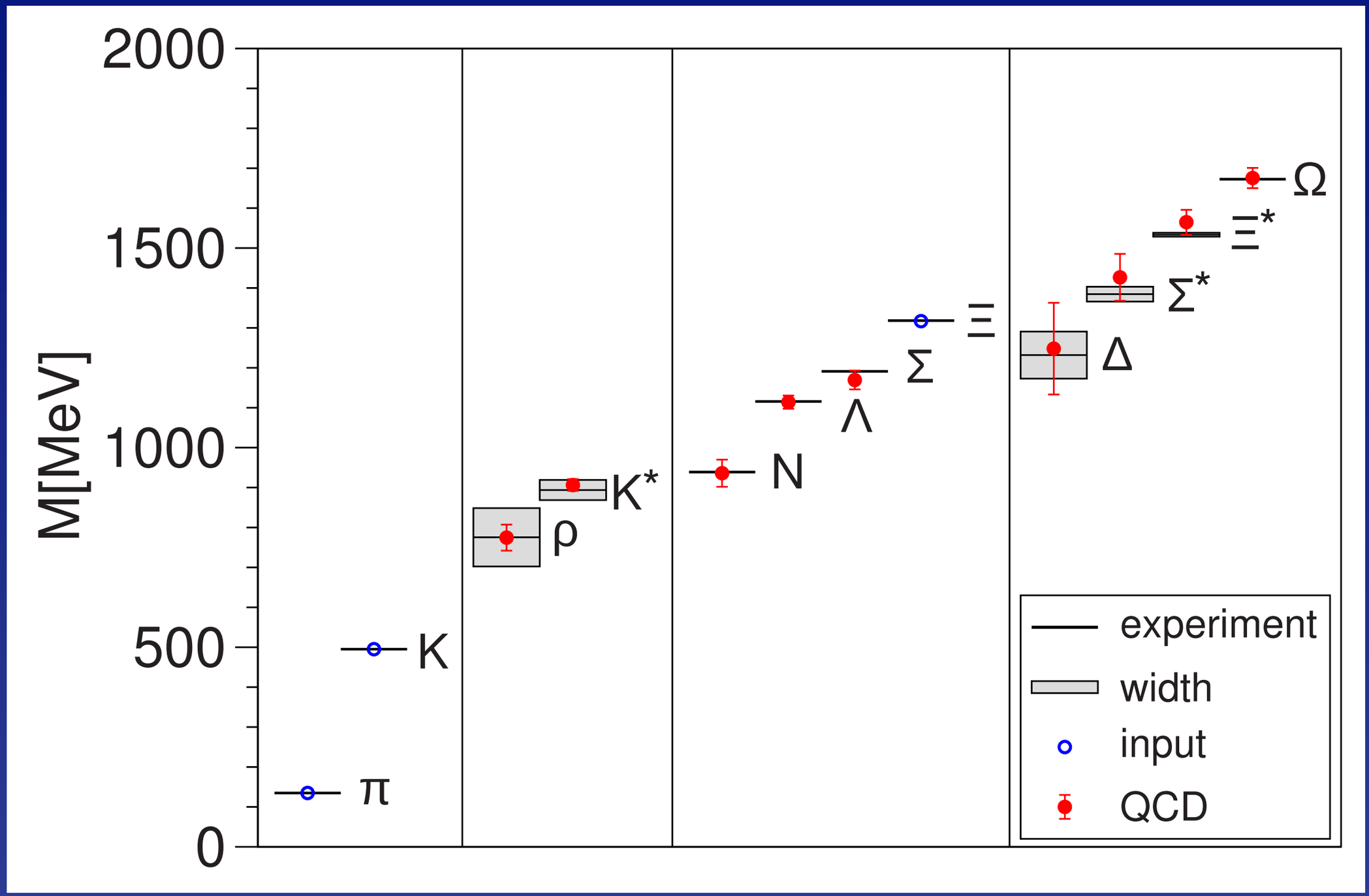
Quarks & gluons confined: evidence, no proof

No structural defects, but *strong CP problem*

Evolution of the strong coupling "constant"



Light hadron spectrum with dynamical fermions



How Might QCD Crack?

(Breakdown of factorization)
Free quarks / unconfined color
New kinds of colored matter
Quark compositeness
Larger color symmetry containing QCD

QCD could be complete, up to M_{Planck}

… but that doesn't prove it must be

Prepare for surprises!

10. SOME EXPERIMENTS ON MULTIPLE PRODUCTION

KENNETH G. WILSON

Laboratory of Nuclear Studies, Cornell University, Ithaca, New York

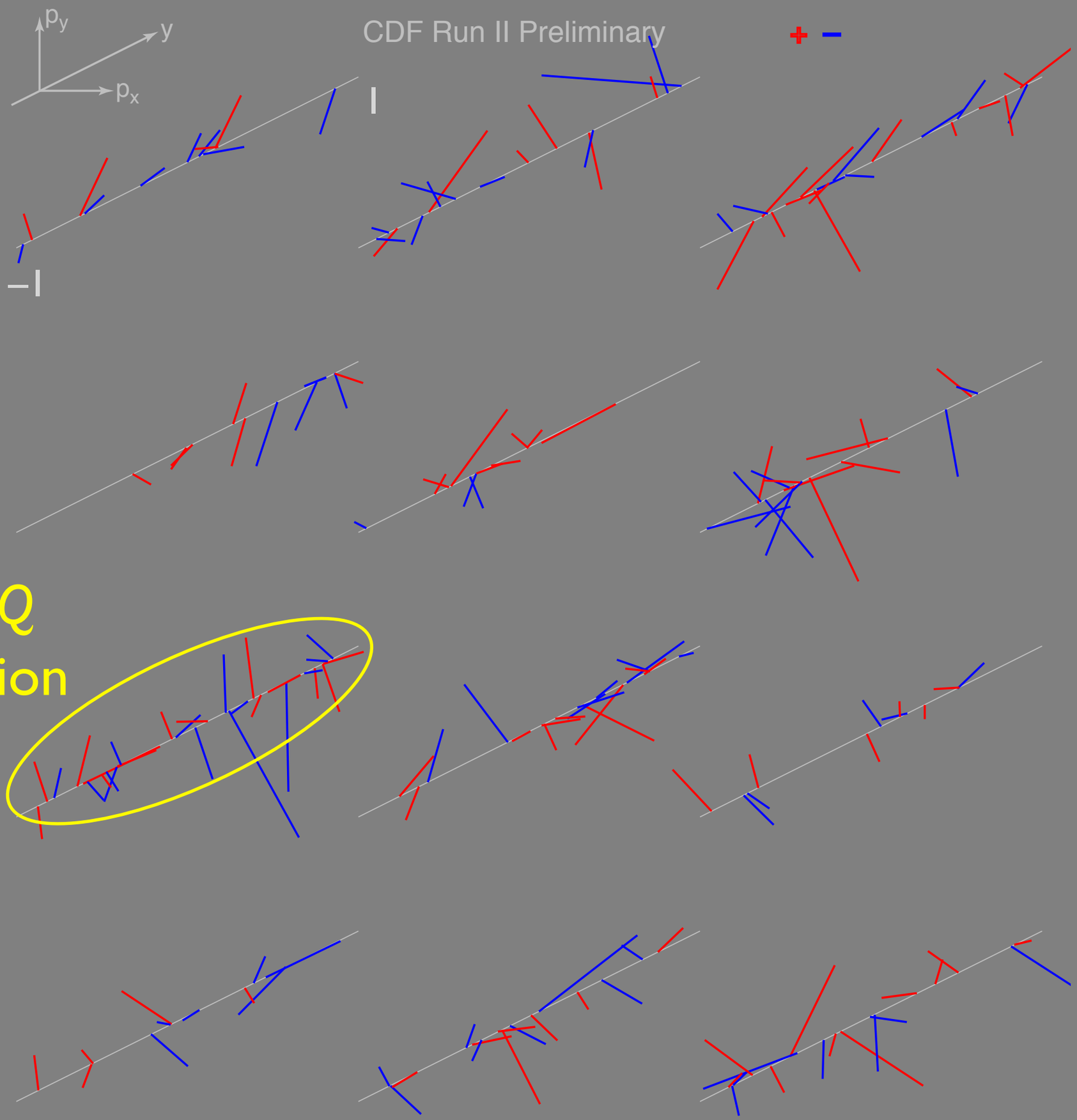
Isn't "Soft" Particle Production Settled Knowledge?

Diffractive scattering + short-range order

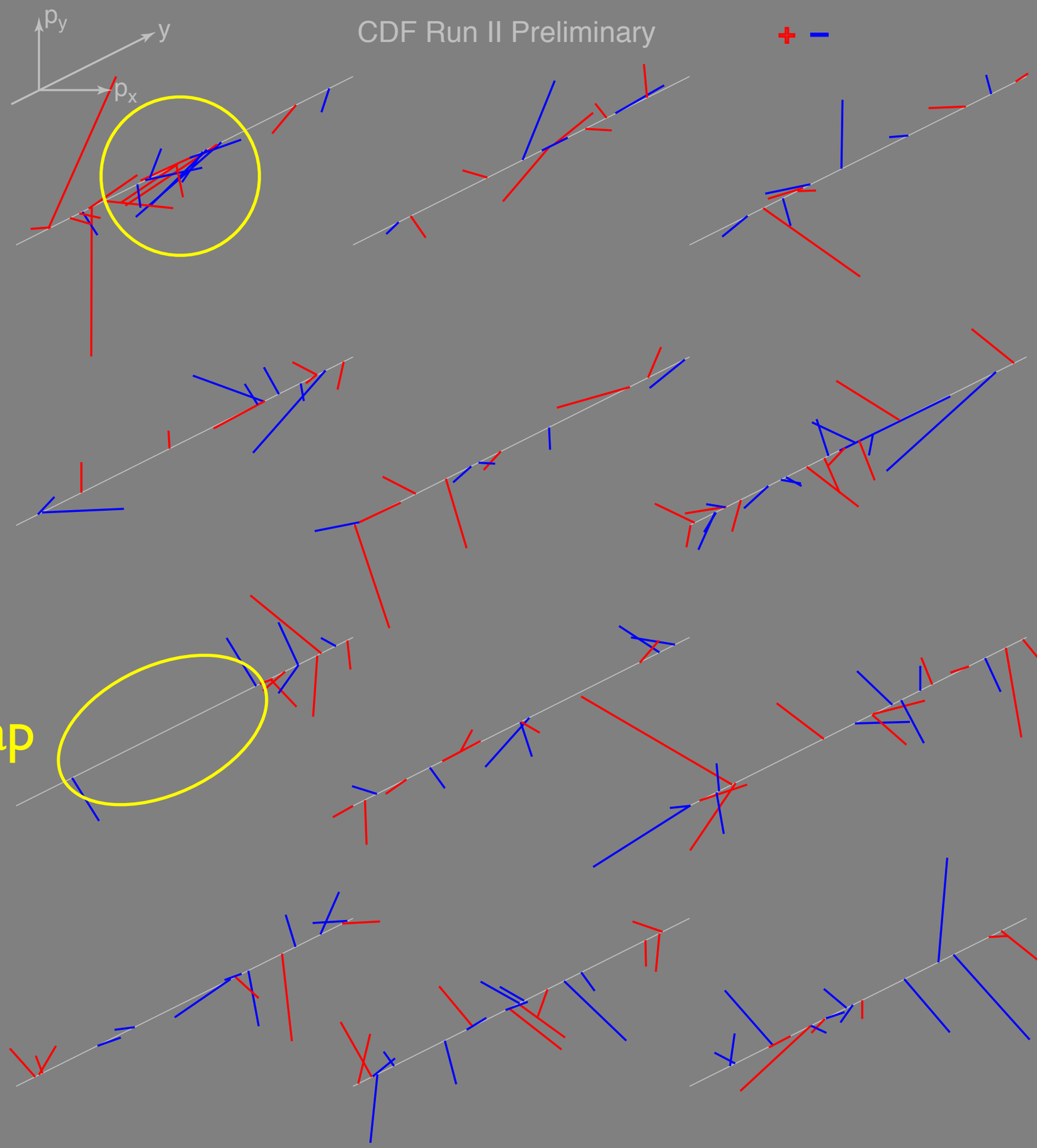
- (Not exhaustively studied at Tevatron)
- Long-range correlations?
- High density of $p_z = 5$ to 10 GeV partons
  $\rightsquigarrow$ hot spots, thermalization, . . . ?
- Multiple-parton interactions, perhaps correlated
  $q(qq)$ in impact-parameter space, . . .
- PYTHIA tunes miss 2.36-TeV data (ATLAS & CMS)

Few percent of minimum-bias events ($\sqrt{s} \gtrsim 1$ TeV)
might display an unusual event structure
We should look! How?

Local $p_\perp$, Q compensation

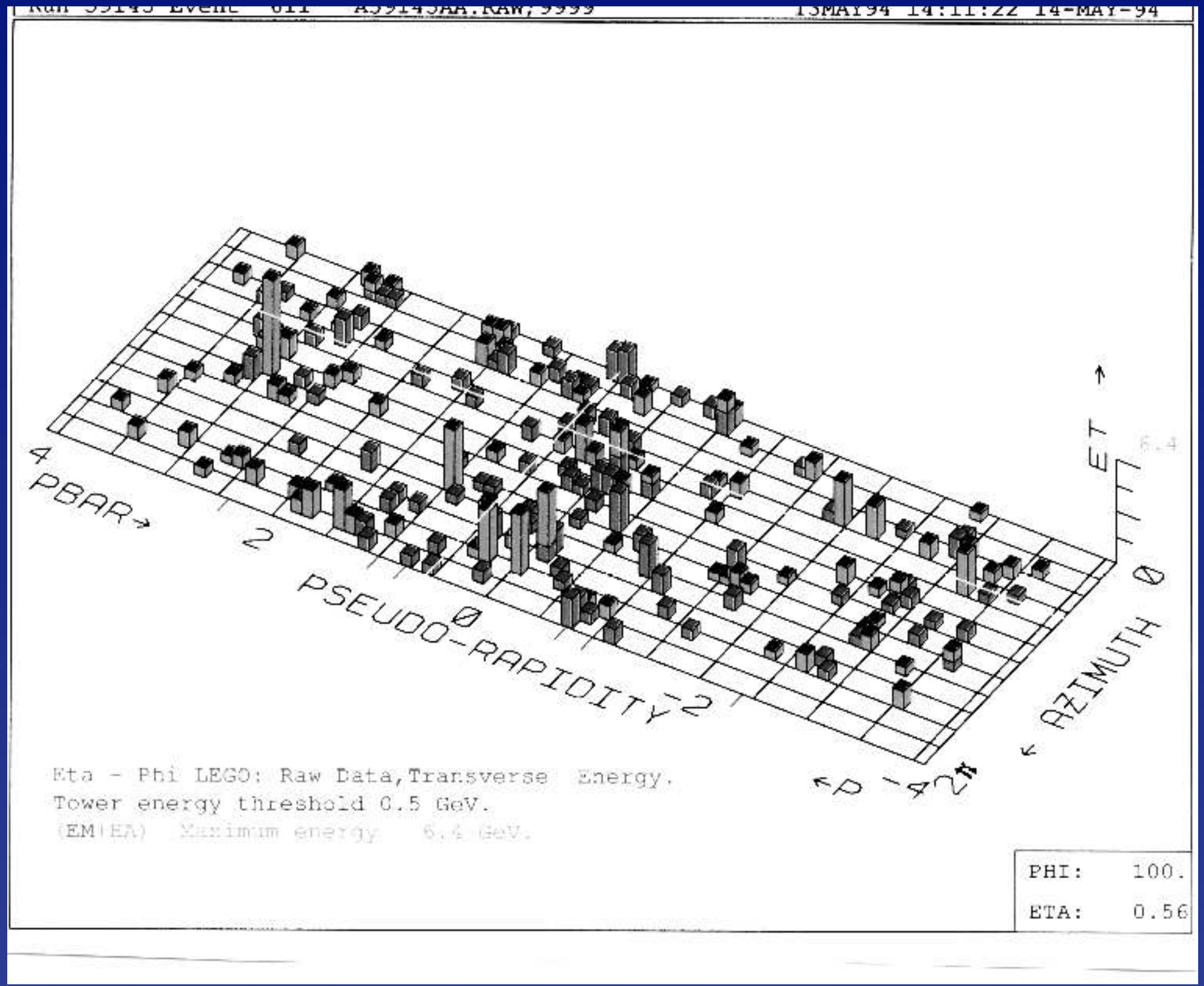


Hot spot?



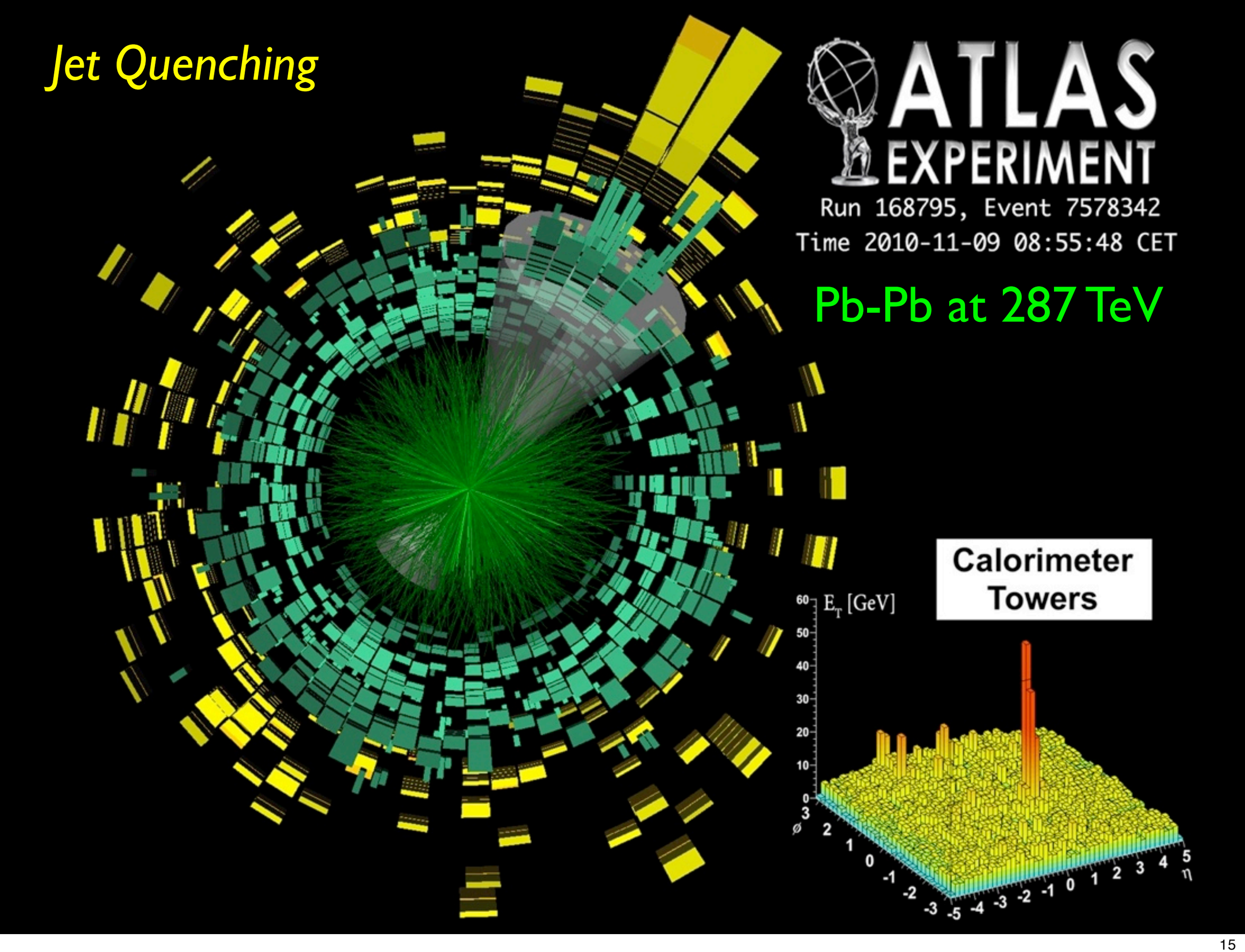
Rapidity gap

Physics in the Weeds: Atypical Event from CDF Run I



> 100 towers above 0.5 GeV, $\sum E_\perp = 320$ GeV

Jet Quenching



Electroweak Theory

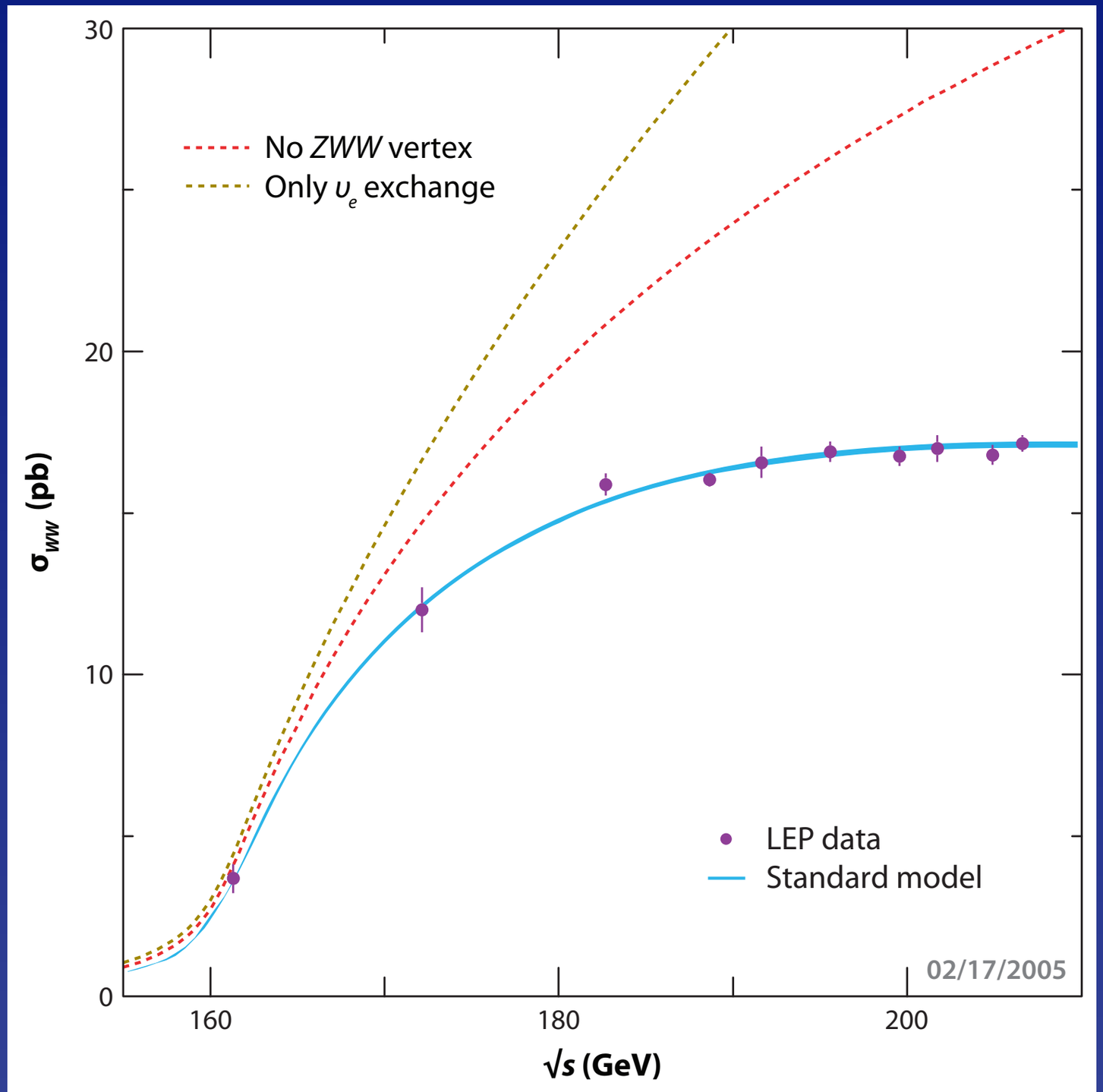
To good approximation …
3-generation V–A
GIM suppresses FCNC
CKM quark-mixing matrix describes CPV

Gauge symmetry validated in $e^+e^- \rightarrow W^+W^-$

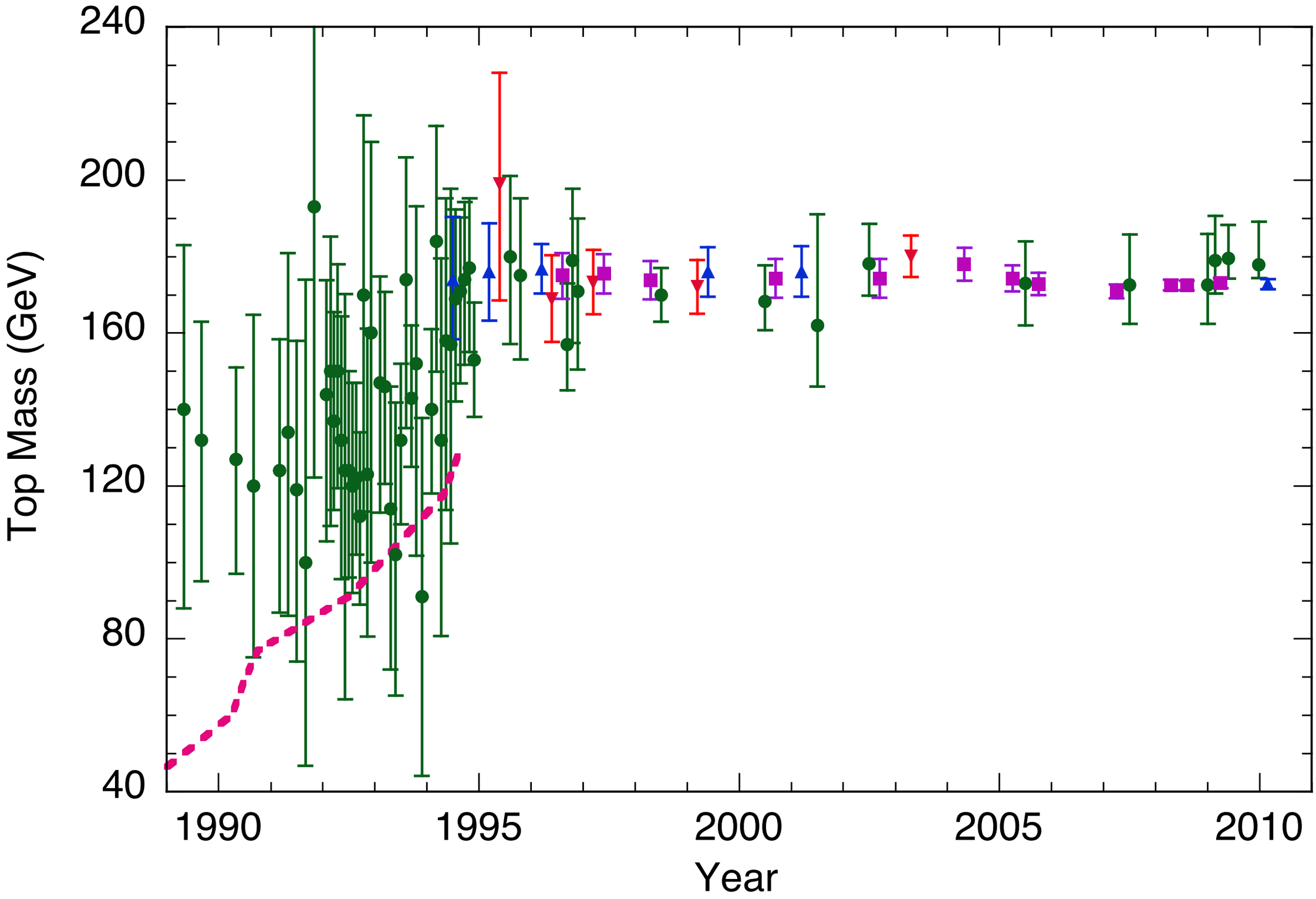
Tested as quantum field theory at per-mille level

Gauge symmetry (group-theory structure) tested in

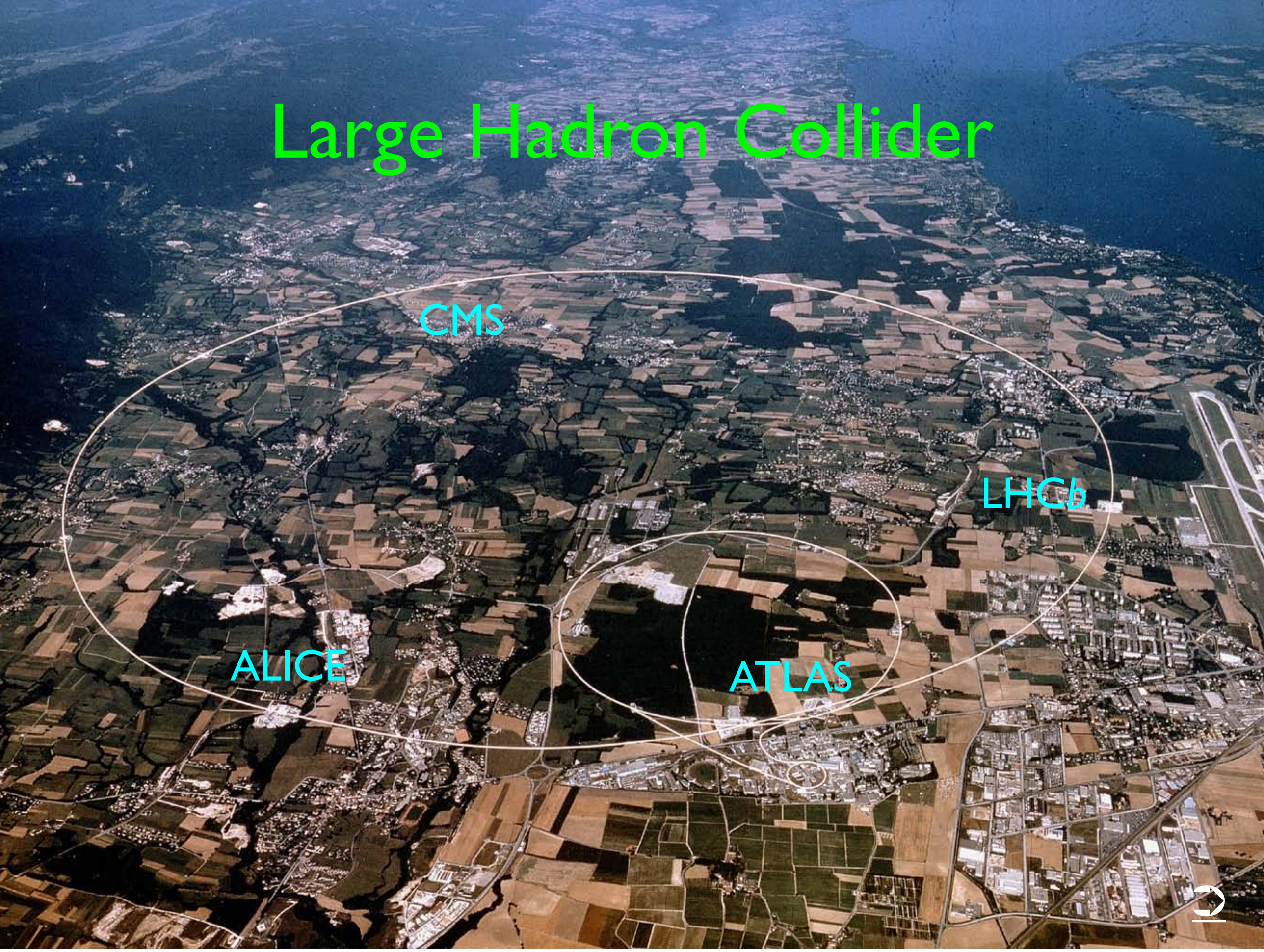
$$e^+e^- \longrightarrow W^+W^-$$

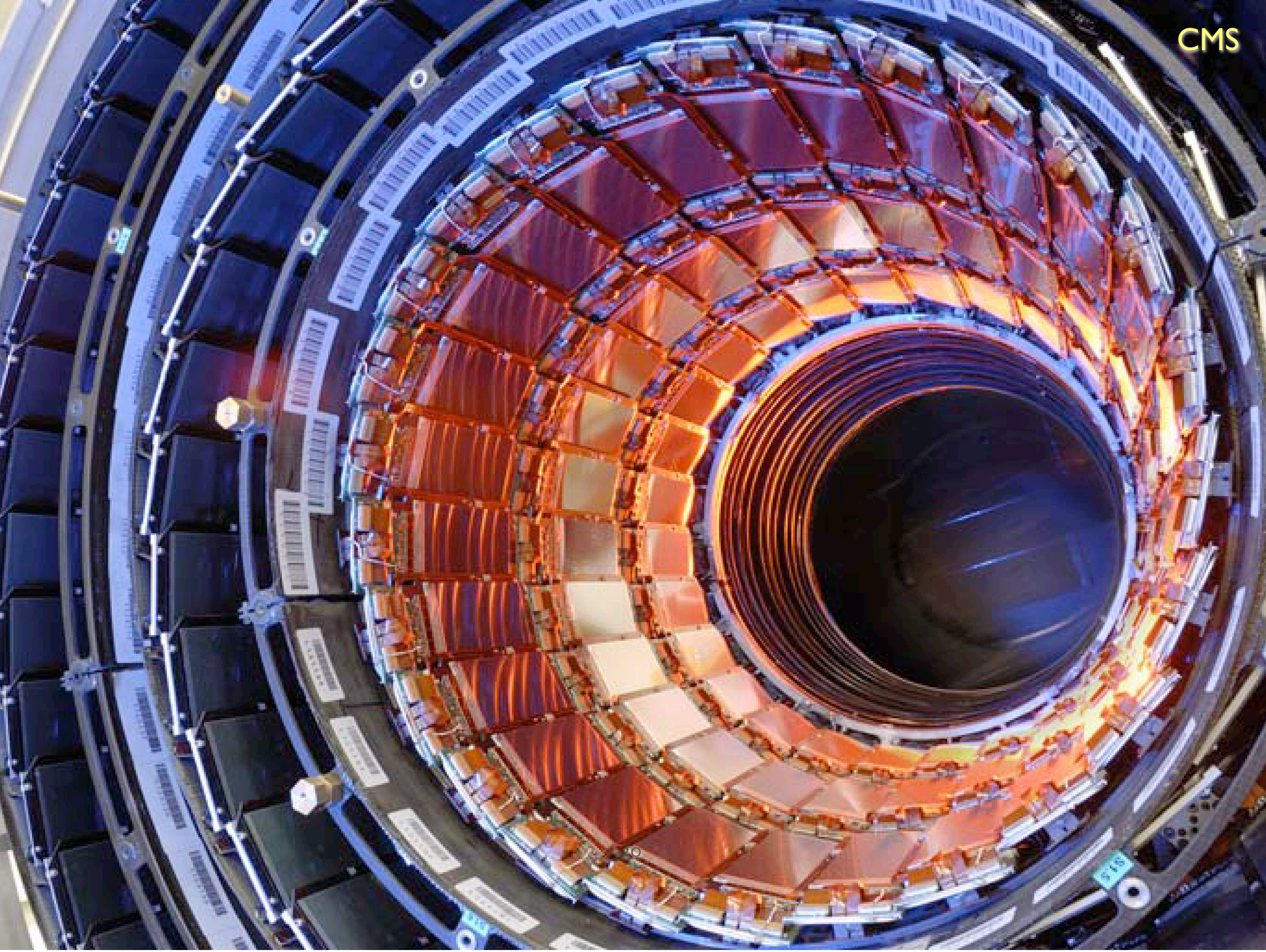


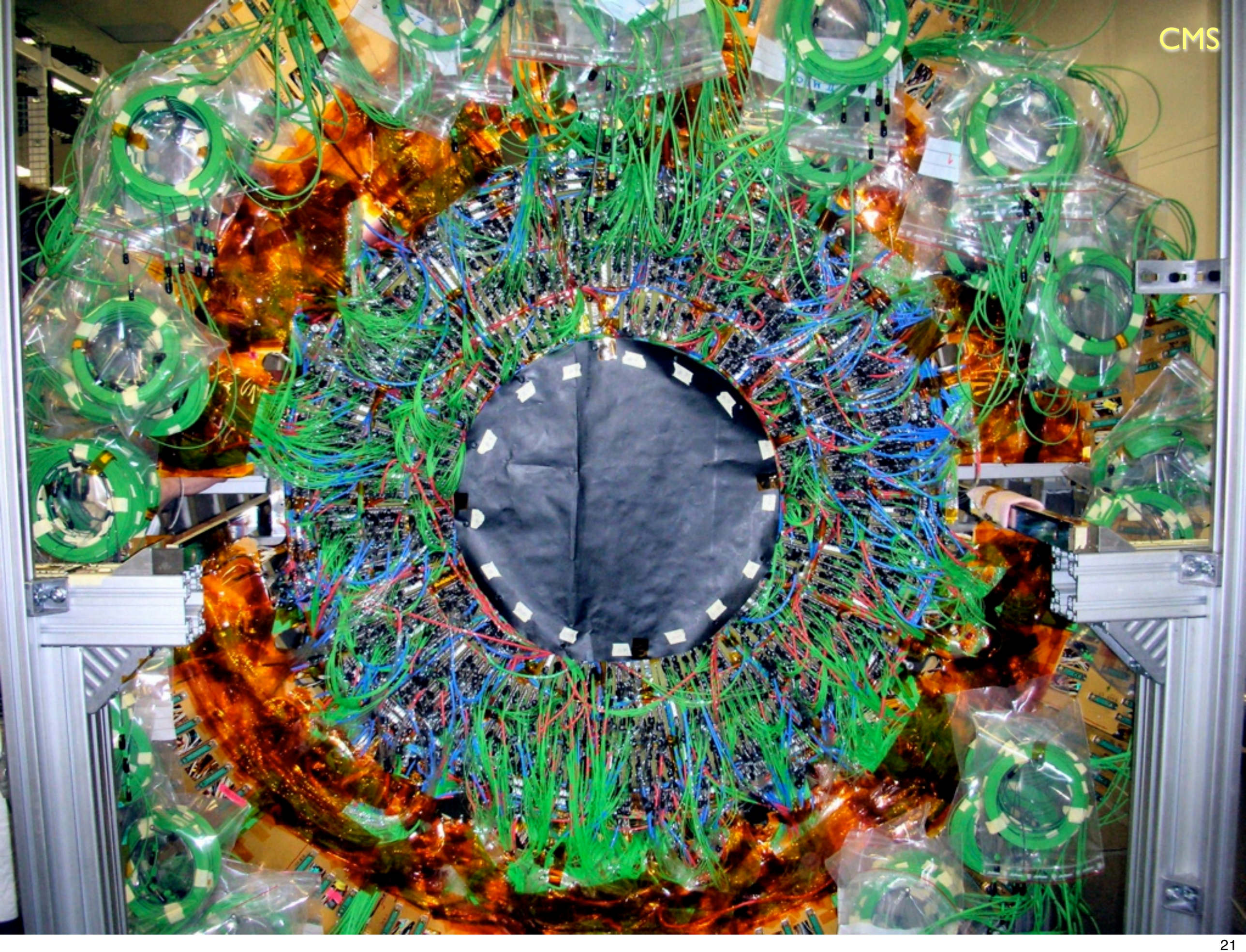
Electroweak Theory Anticipates Discoveries



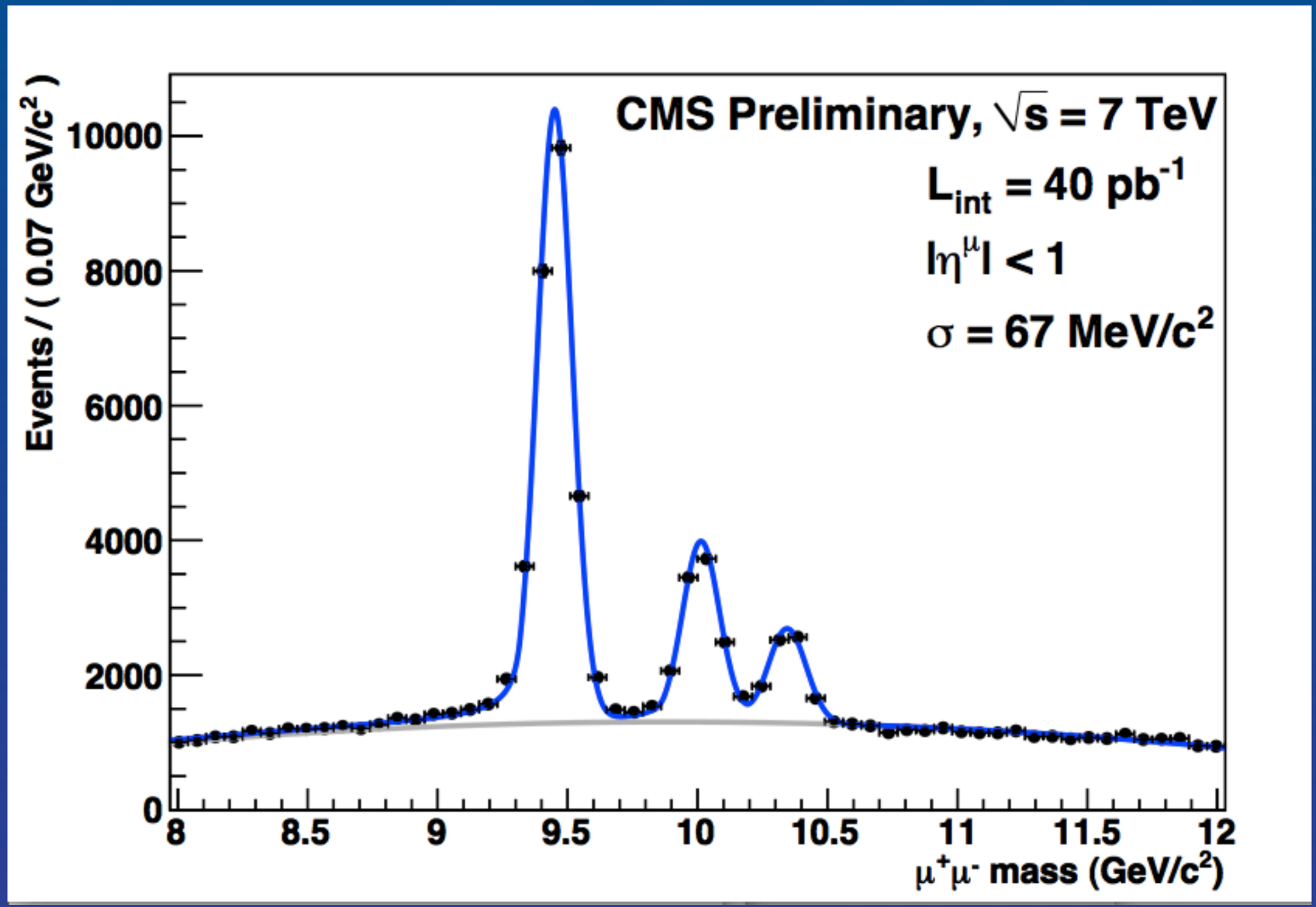
Large Hadron Collider

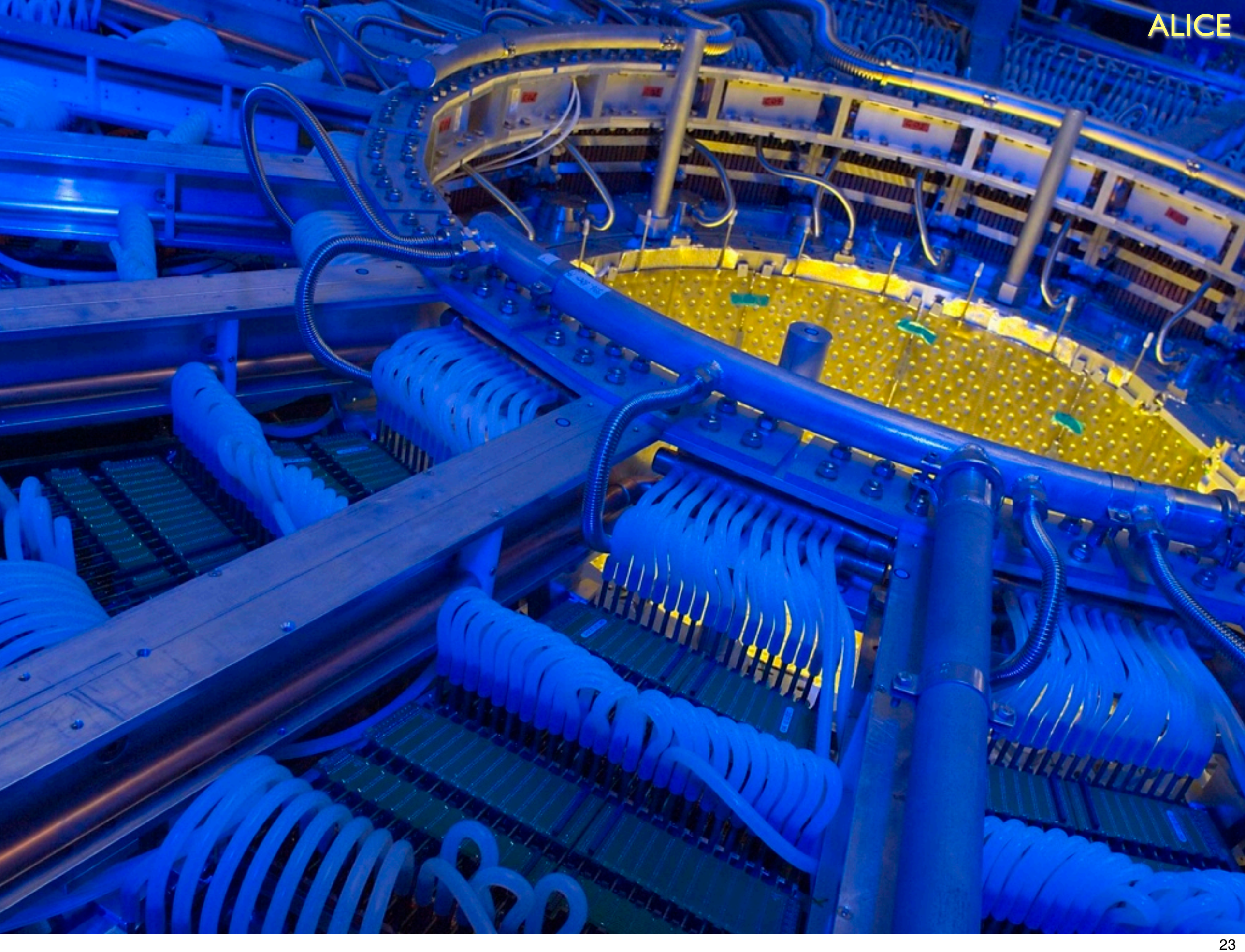



CMS

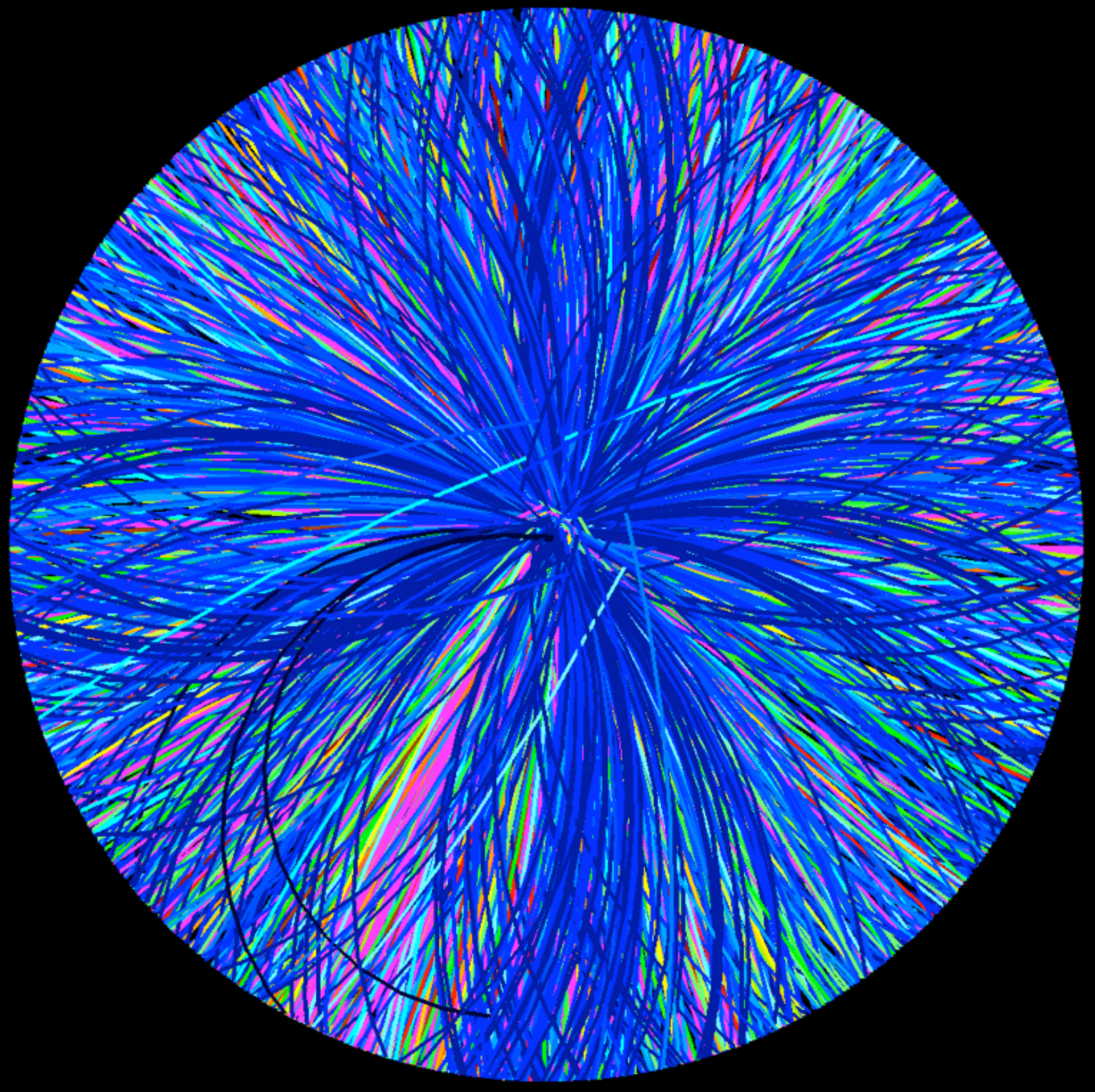

CMS

ϒ Spectrum


CMS Preliminary, √s = 7 TeV
L_int = 40 pb^-1
|η^μ| < 1
σ = 67 MeV/c^2
Events / (0.07 GeV/c^2)
10000
8000
6000
4000
2000
0
8
8.5
9
9.5
10
10.5
11
11.5
12
μ^+μ^- mass (GeV/c^2)

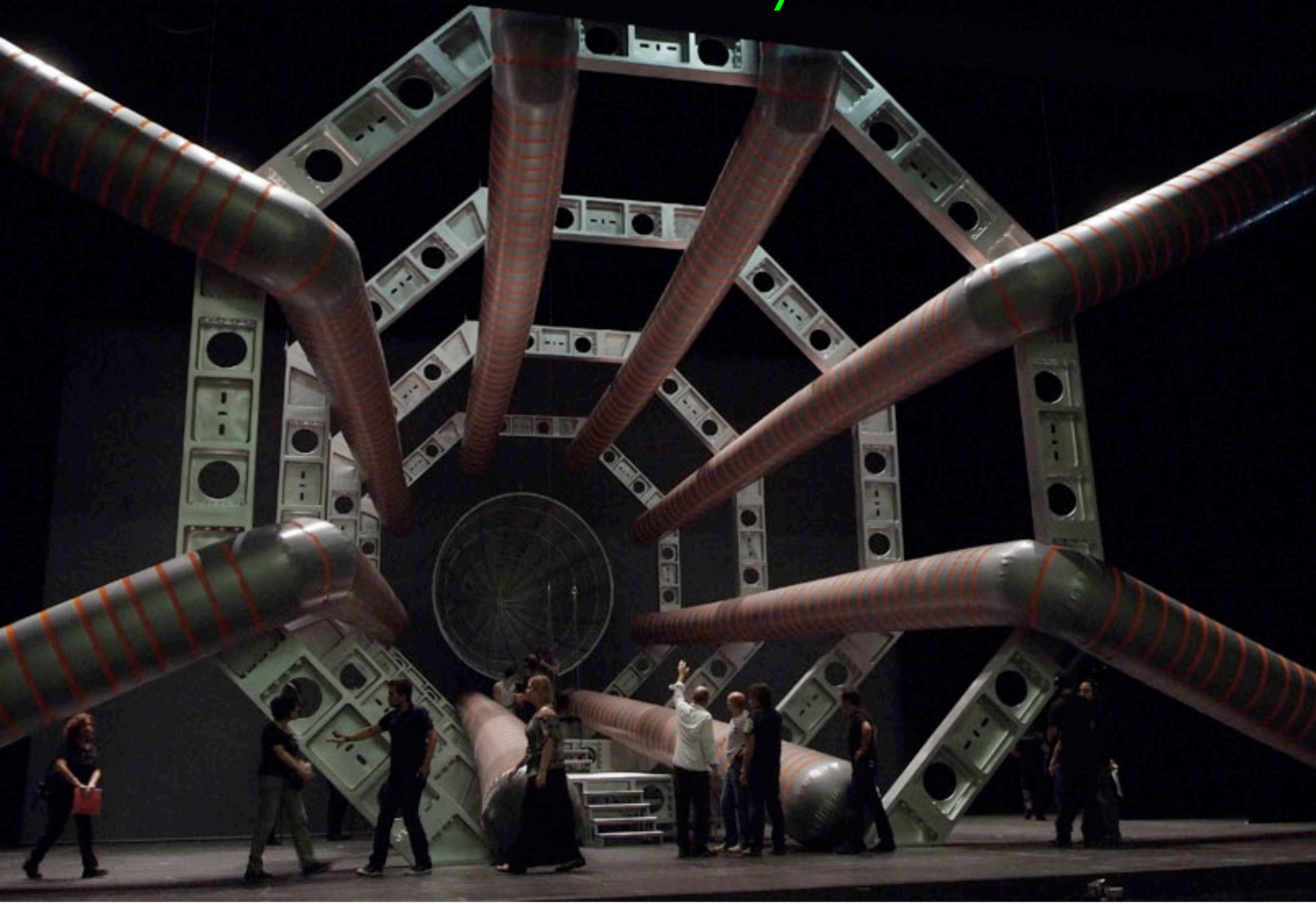


ALICE Experiment: Pb-Pb Collisions at 287 TeV




LHCb

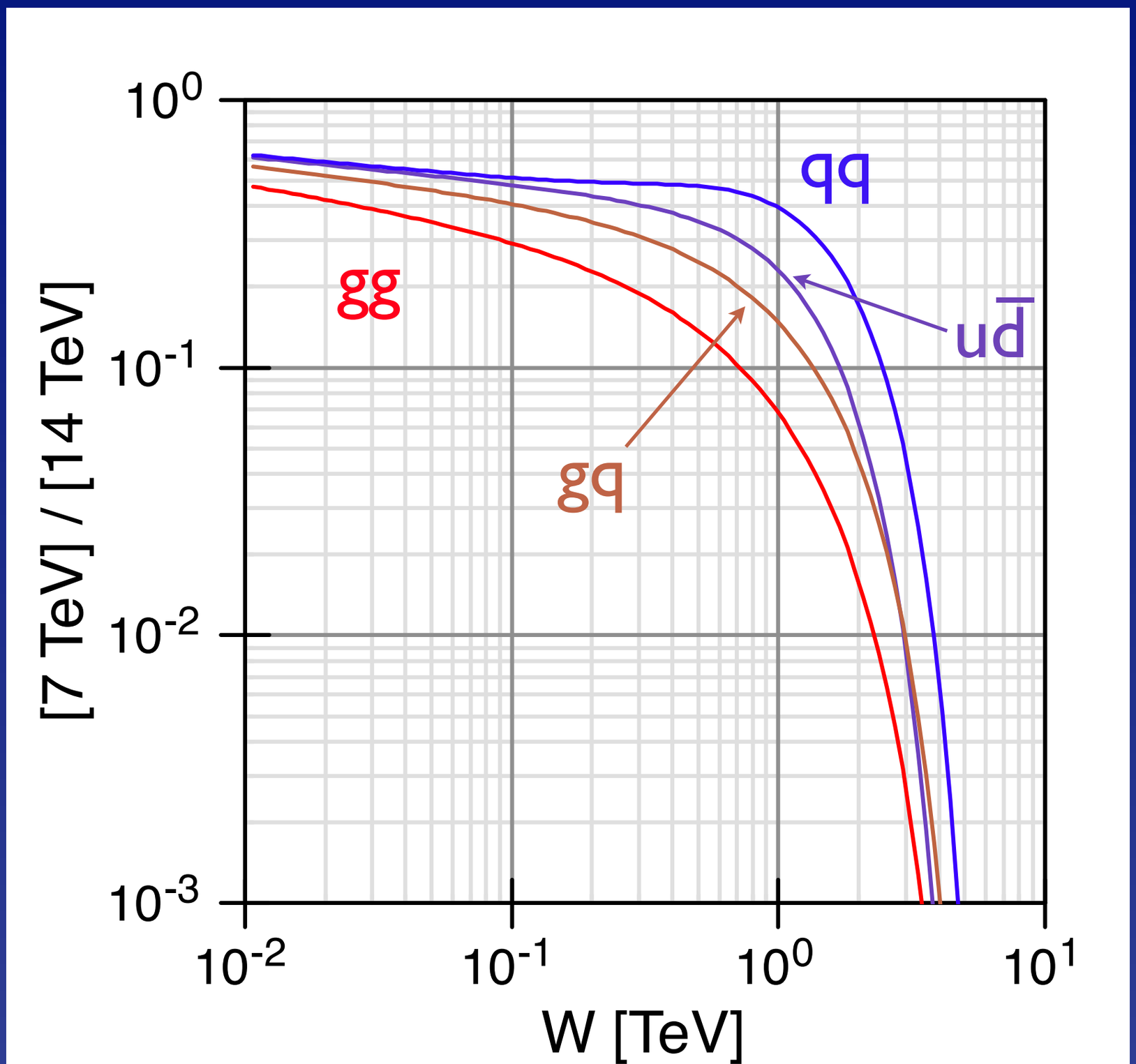
Hector Berlioz · *Les Troyens* · Valencia



Wonderful progress …
… but miles to go:

Beam energy x 2
Luminosity x 100

Ratios of Parton Luminosities

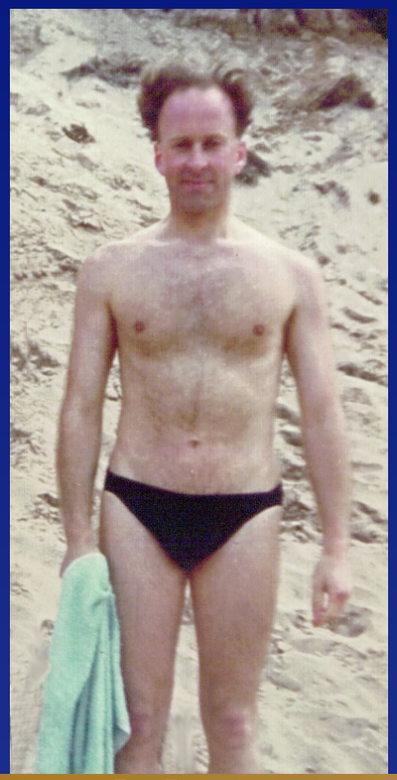


An unknown agent hides electroweak symmetry

- A force of a new character, based on interactions of an elementary scalar
- A new gauge force, perhaps acting on undiscovered constituents
- A residual force that emerges from strong dynamics among electroweak gauge bosons
- An echo of extra spacetime dimensions

Spontaneous Breaking of Gauge Symmetry (1964)

Higgs (then)



Kibble Guralnik Hagen Englert Brout

The Importance of the 1-TeV Scale

EW theory does not predict Higgs-boson mass

Thought experiment: *conditional upper bound*

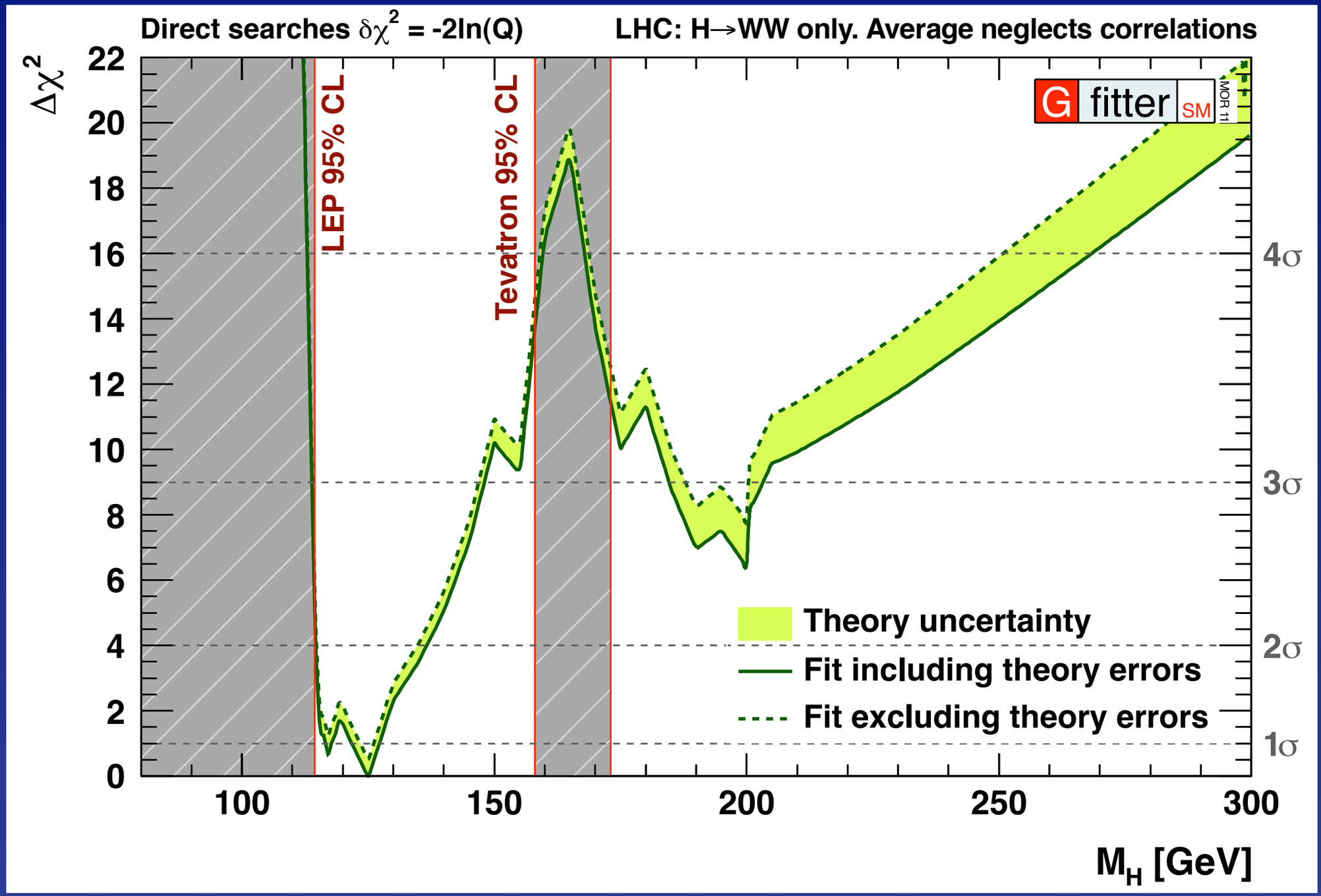
W^+W^-, ZZ, HH, HZ satisfy s-wave unitarity,

provided $\boxed{M_H \leq (8\pi\sqrt{2}/3G_F)^{1/2} \approx 1\ \text{TeV}}$

- If bound is respected, perturbation theory is "everywhere" reliable
- If not, weak interactions among $W^\pm$, Z, H become strong on 1-TeV scale

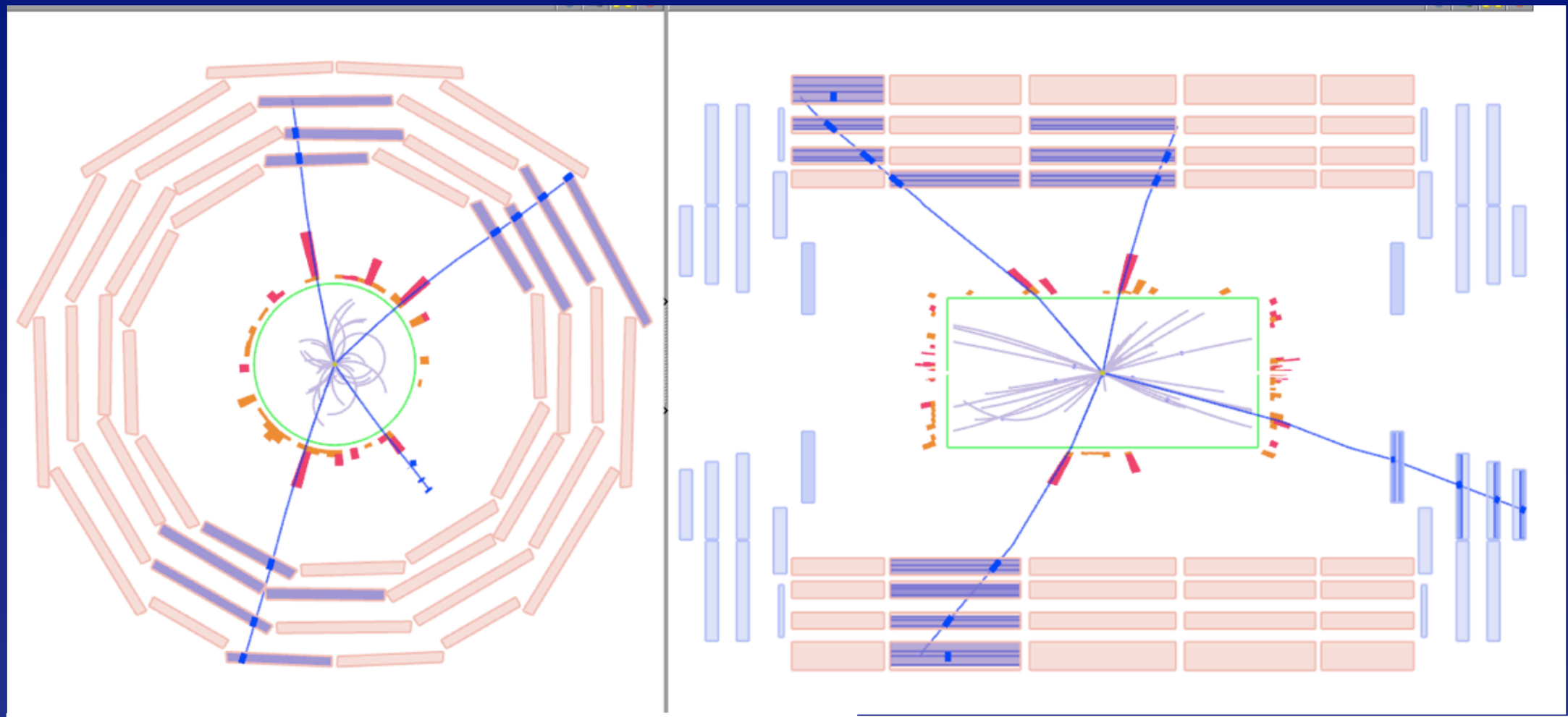
New phenomena are to be found around 1 TeV

Where the SM Higgs Boson Is Not



BSM: Heavy Higgs allowed, even natural

How a heavy Higgs boson would appear



CMS event: 7-TeV pp

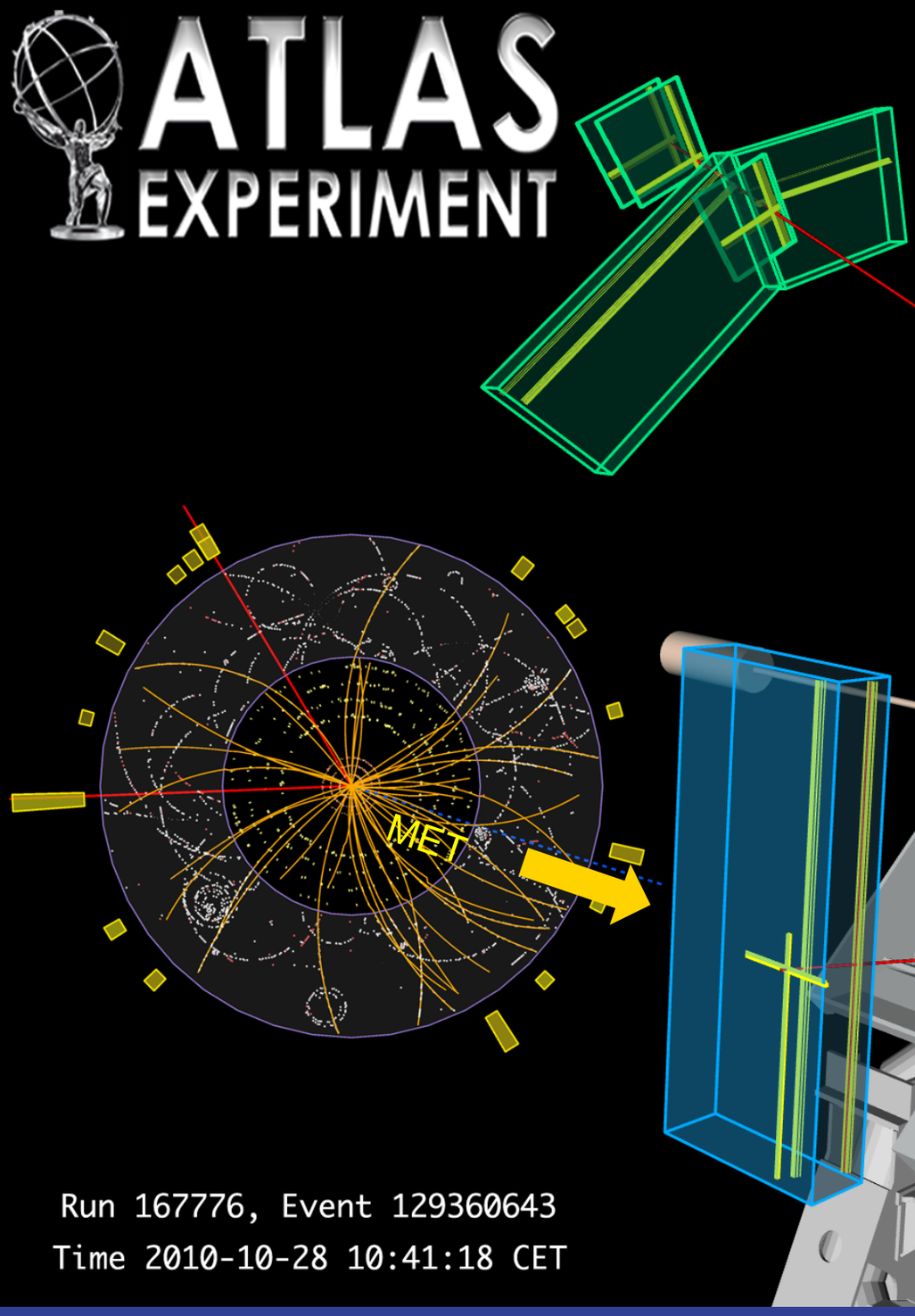
Invariant Masses

$\mu_0 + \mu_1$: 92.15 GeV (total(Z) p_T 26.5 GeV, ϕ -3.03),
$\mu_2 + \mu_3$: 92.24 GeV (total(Z) p_T 29.4 GeV, ϕ +.06),
$\mu_0 + \mu_2$: 70.12 GeV (total p_T 27 GeV),
$\mu_3 + \mu_1$: 83.1 GeV (total p_T 26.1 GeV).

Invariant Mass of 4μ: 201 GeV

A ZZ→μμνν Candidate in ATLAS Data

$M_{\mu\mu}$ = 94 GeV, E_T^{miss} = 161 GeV



2011-2012 Standard-Model Higgs Projections

SM Higgs Search Prospects (Mass in GeV)			
ATLAS + CMS ≈ 2 x CMS	95% CL exclusion	3 σ sensitivity	5 σ sensitivity
1 fb^{-1}	120 - 530	135 - 475	152 - 175
2 fb^{-1}	114 - 585	120 - 545	140 - 200
5 fb^{-1}	114 - 600	114 - 600	128 - 482
10 fb^{-1}	114 - 600	114 - 600	117 - 535

V. Sharma, Moriond EW 2011

Why will it matter?

Imagine a world without a symmetry-breaking (Higgs) mechanism at the electroweak scale

Without a Higgs mechanism …

Electron and quarks would have no mass

QCD would confine quarks into protons, etc.

Nucleon mass little changed

Surprise: QCD would hide EW symmetry,

give tiny masses to W, Z

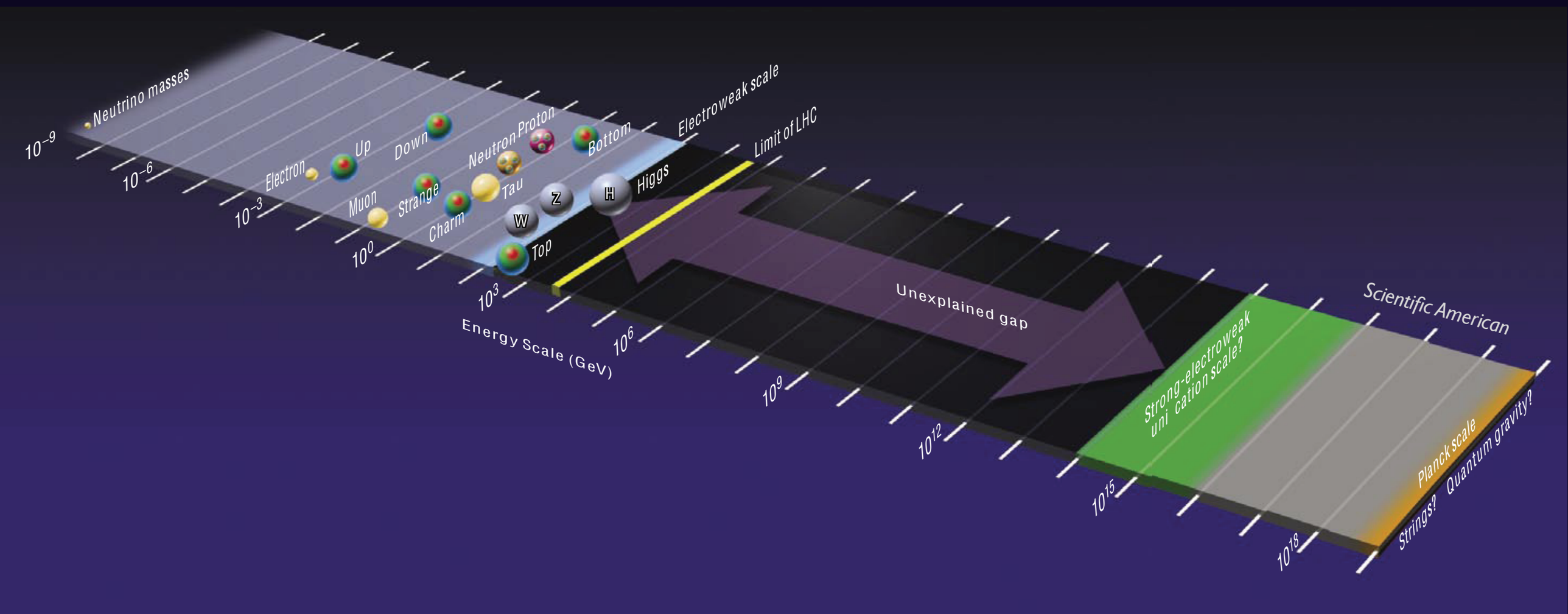
Massless electron: atoms lose integrity

No atoms means no chemistry, no stable composite structures like liquids, solids, …

arXiv:0901.3958

Does M_H < 1 TeV make sense?

The peril of quantum corrections



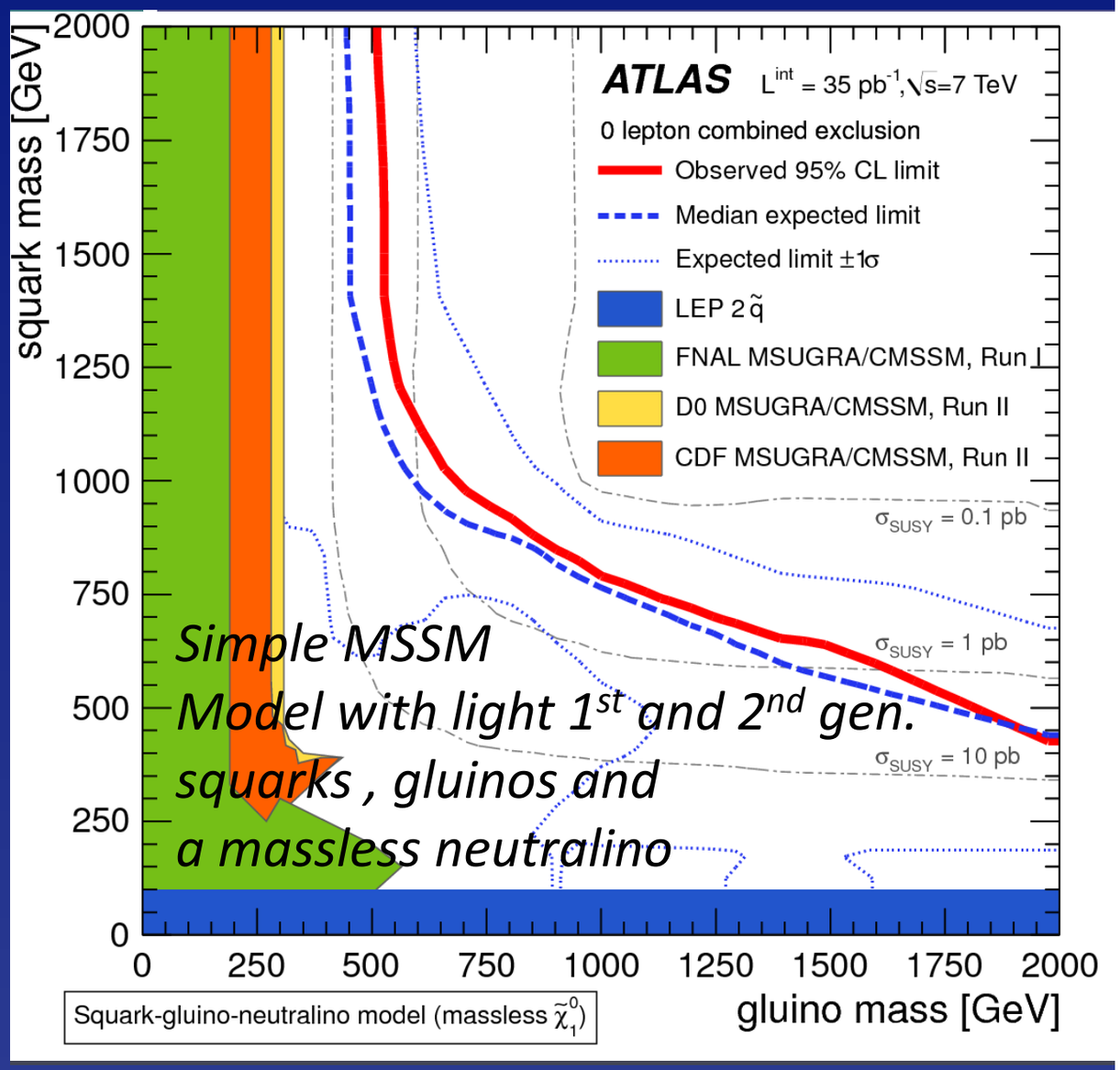
Puzzle #1: Expect New Physics on TeV scale
to stabilize Higgs mass, solve hierarchy problem,
but no sign of FCNC

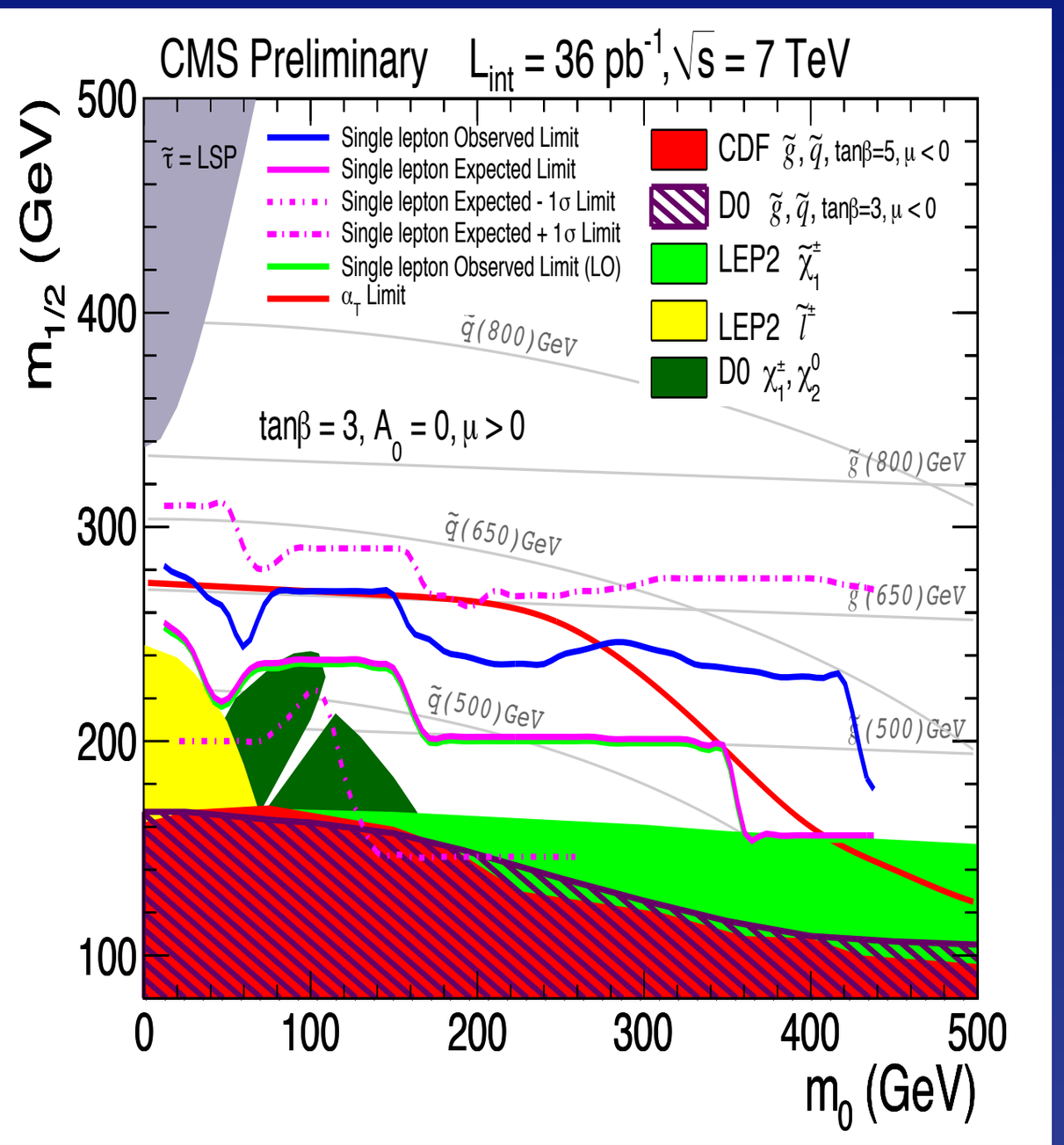
Minimal flavor violation a name, not yet an answer

Great interest in searches for
forbidden or suppressed processes

Puzzle #2: Expect New Physics on TeV scale
to stabilize Higgs mass, solve hierarchy problem,
but no quantitative failures of EW theory

Supersymmetry is hiding very effectively





… and nothing else has turned up in early running

A particularly demanding assessment

Strumia, Moriond EW 2011

Several persistent tensions in flavor sector

New physics in B mixing?

4th generation?
Supersymmetry?
Extra dimensions?
… ?

$|V_{ub}|$ comparisons

Latest combined fit to data,lattice $B \to \pi \ell \nu$ $(2.95 \pm 0.31) \times 10^{-3}$

Inclusive, PDG2010 average: $b \to u \ell \nu$ $(4.37 \pm 0.39) \times 10^{-3}$

$\Big\} 2.7\sigma$

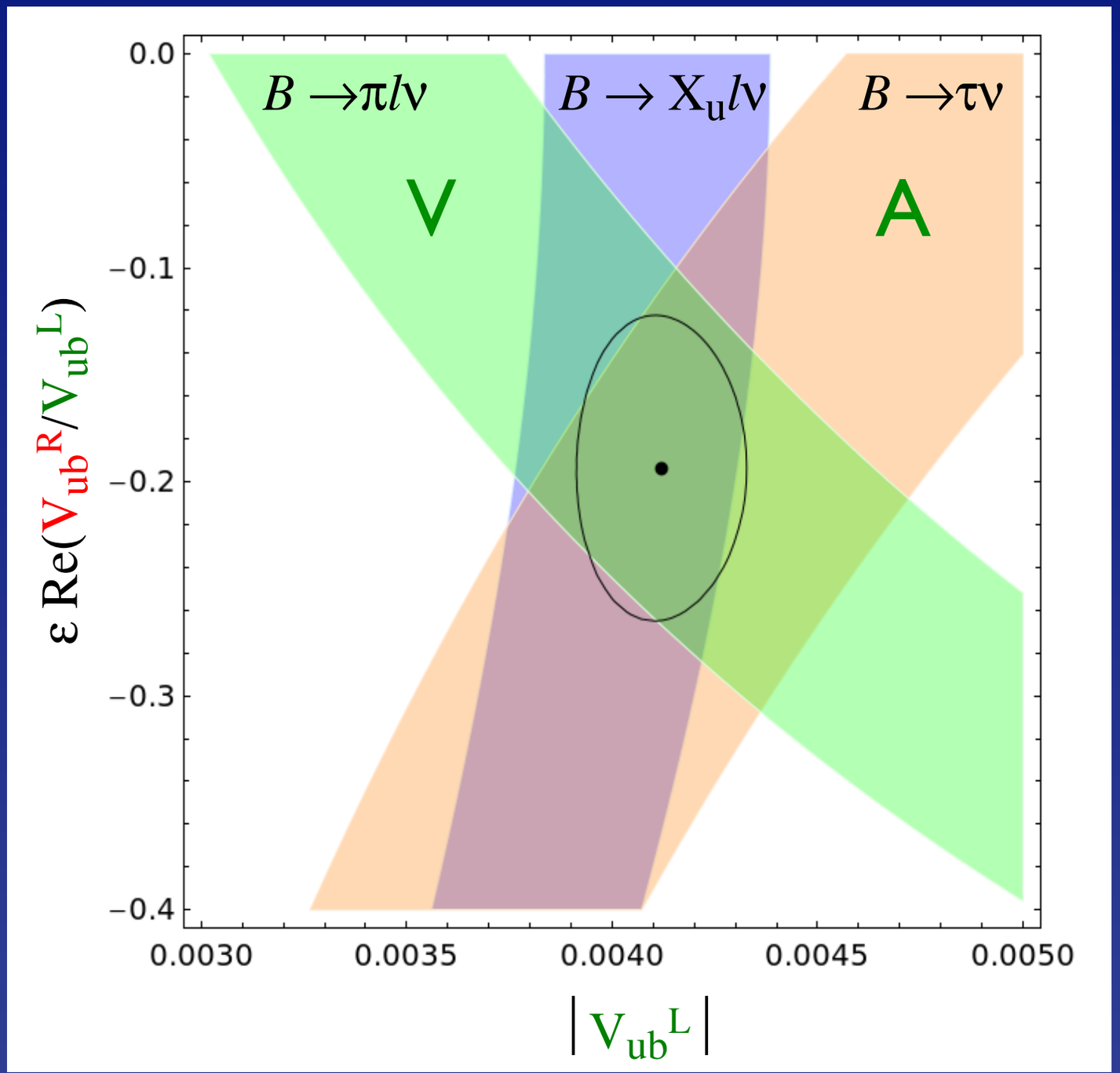
Difference is a problem and perhaps should be identified as an unattributed uncertainty

- work of multiple experiments, multiple theoretical groups.
- exclusive result relies on non-perturbative normalization input
- inclusive result uses m_b, non-perturbative extrapolations and perturbative corrections

Predictions from CKM fits:

UTFit	**3.48±0.16**	**(ICHEP 2008)**
CKMFitter	**$3.51 \pm {}^{0.15}_{0.16}$**	**(Beauty 2009)**

Resolution by RH current?

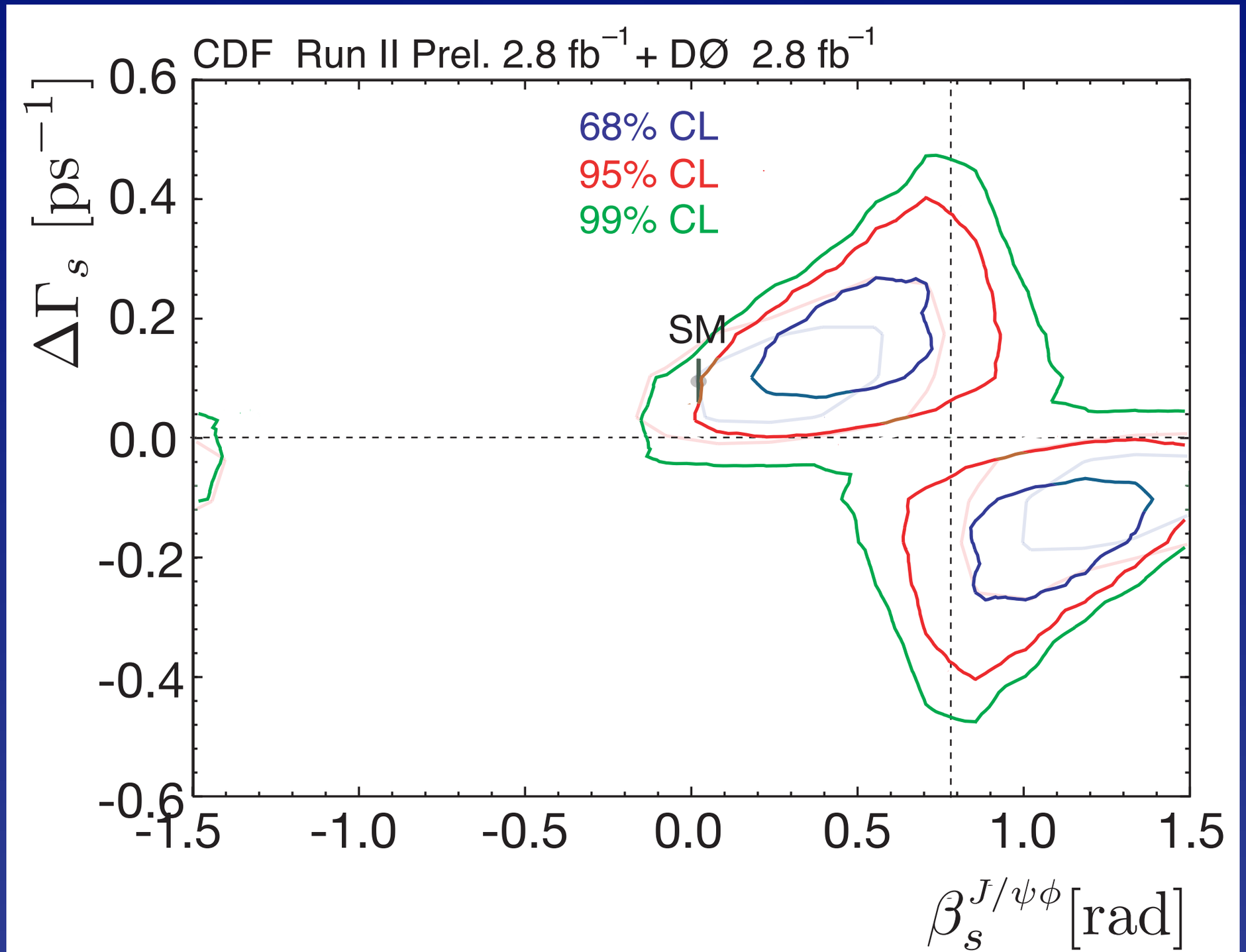


Buras/Gemmler/Isidori 1007.1993

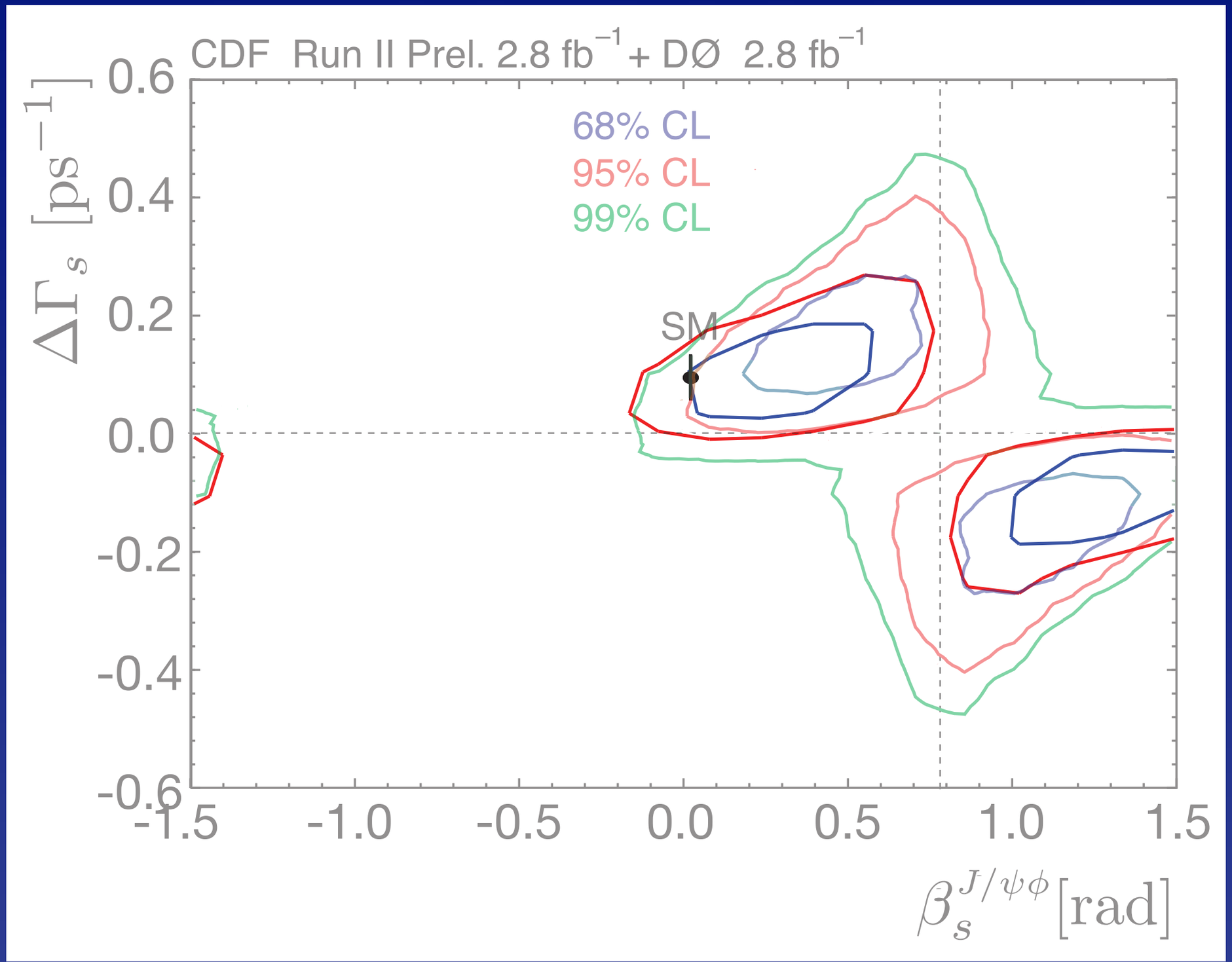
Tevatron puzzles:

DØ Dimuon Charge Asymmetry
CDF top-pair FB Asymmetry
φ J/ψ Phase

CDF/DØ 2009

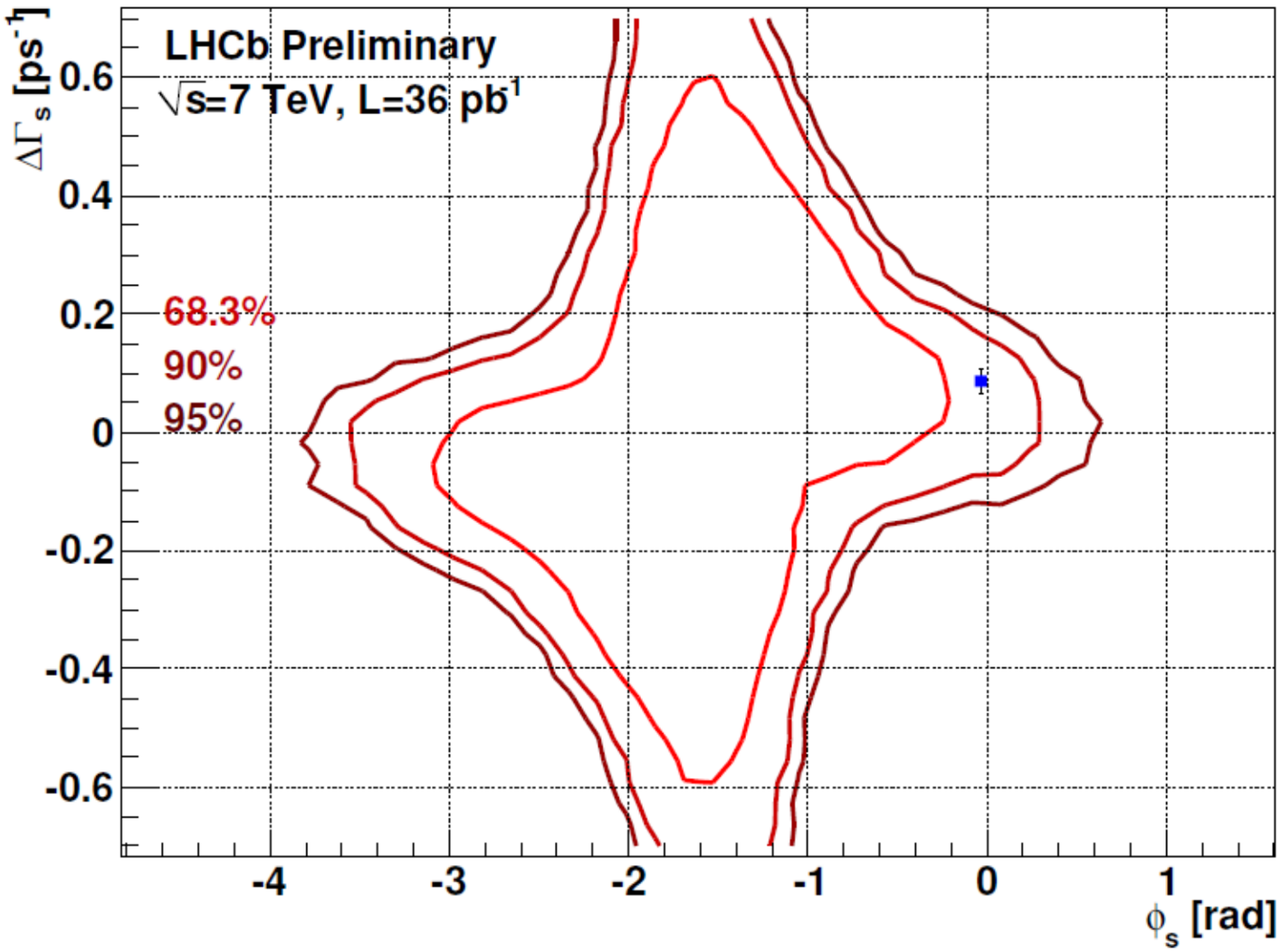

CDF Run II Prel. 2.8 fb^{-1} + DØ 2.8 fb^{-1}
68% CL
95% CL
99% CL
SM
$\Delta\Gamma_s$ [ps^{-1}]
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
$\beta_s^{J/\psi\phi}$[rad]

CDF/DØ 2009 + CDF Update



Constraints on phase ϕ_s

LHCb-Conf-2011-006

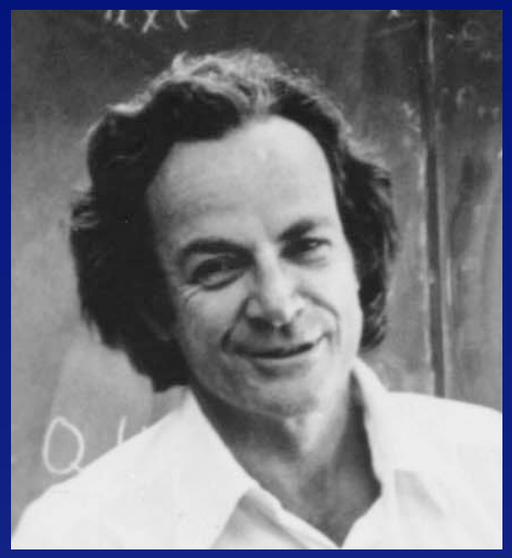


- No meaningful point-estimate
  ⇒ Confidence contours using **Feldman-Cousins method**.
- **Statistical error only**: Accounts for syst. uncertainty of tagging (small).
- Compared to statistical error all systematic effects are negligible

← SM *P*-value: 22% ("1.2σ")

$\phi_s \in [\,-2.7,\ -0.5]$ rad at 68% CL
$\phi_s \in [\,-3.5,\ 0.2\,]$ rad at 95% CL

Standard Model:
$\Delta\Gamma_s = 0.087 \pm 0.021$ ps-1
(A.Lenz, U.Nierste. arXiv:1102.4274)
$\phi_s = -0.0363 \pm 0.0017$ rad (CKMfitter)



Why does the muon weigh?

gauge symmetry allows

$$\zeta_e \left[(\overline{e_{\mathsf{L}}} \Phi) e_{\mathsf{R}} + \overline{e_{\mathsf{R}}} (\Phi^\dagger e_{\mathsf{L}}) \right] \rightsquigarrow m_e = \zeta_e v/\sqrt{2}$$

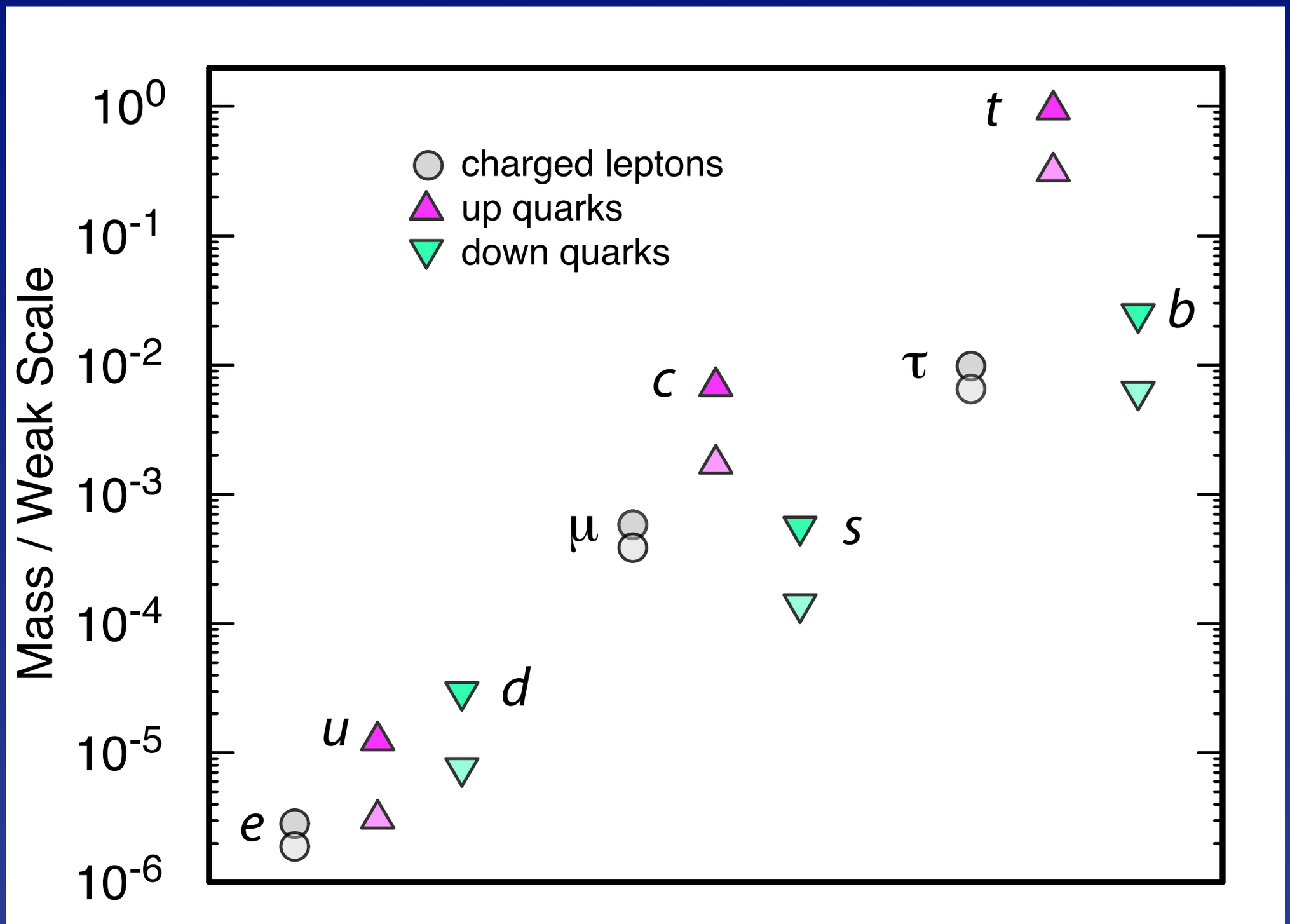
after SSB

What does the muon weigh?

ζ_e : picked to give right mass, not predicted

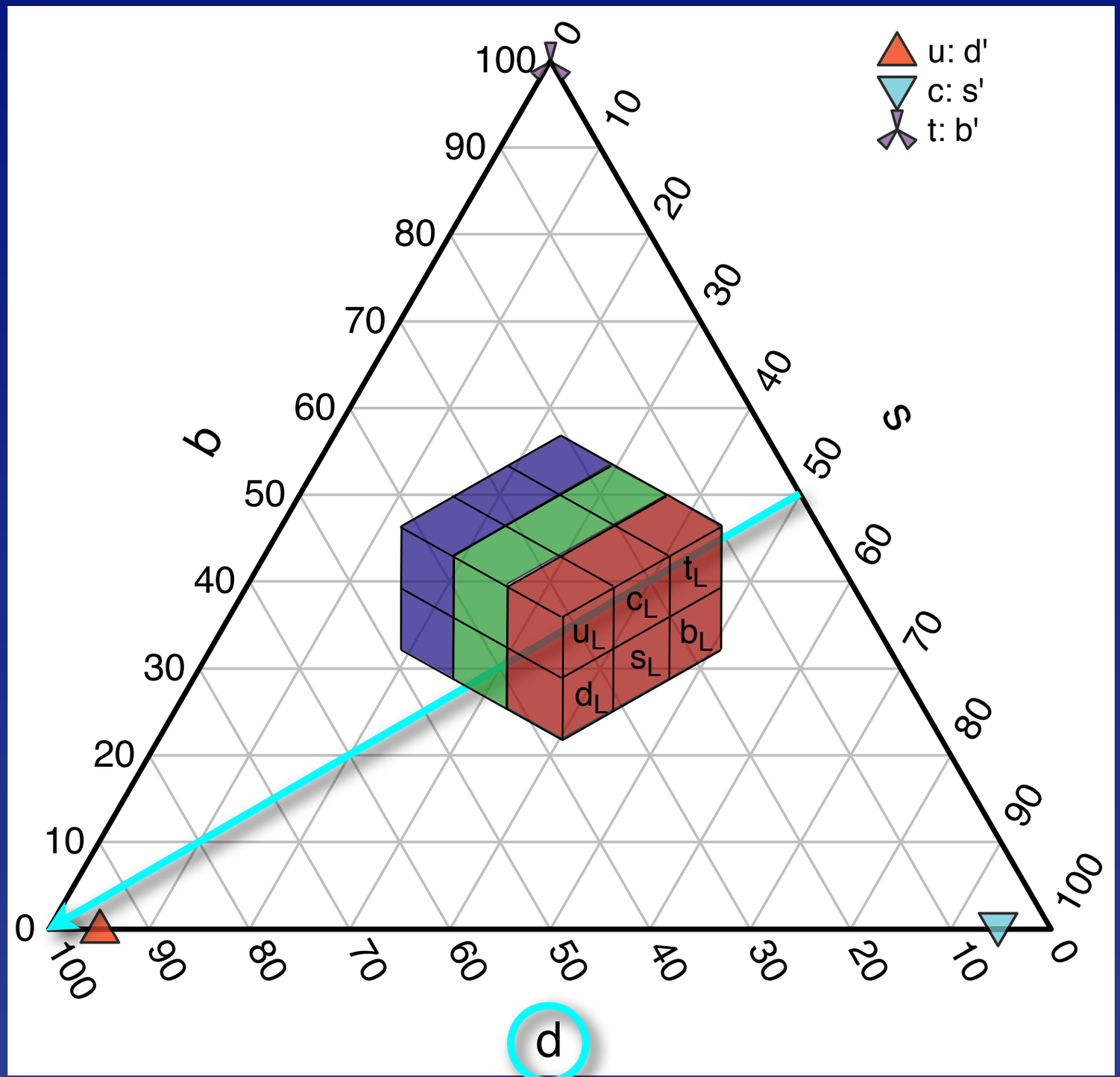
fermion mass implies physics beyond the standard model

Fermion Masses



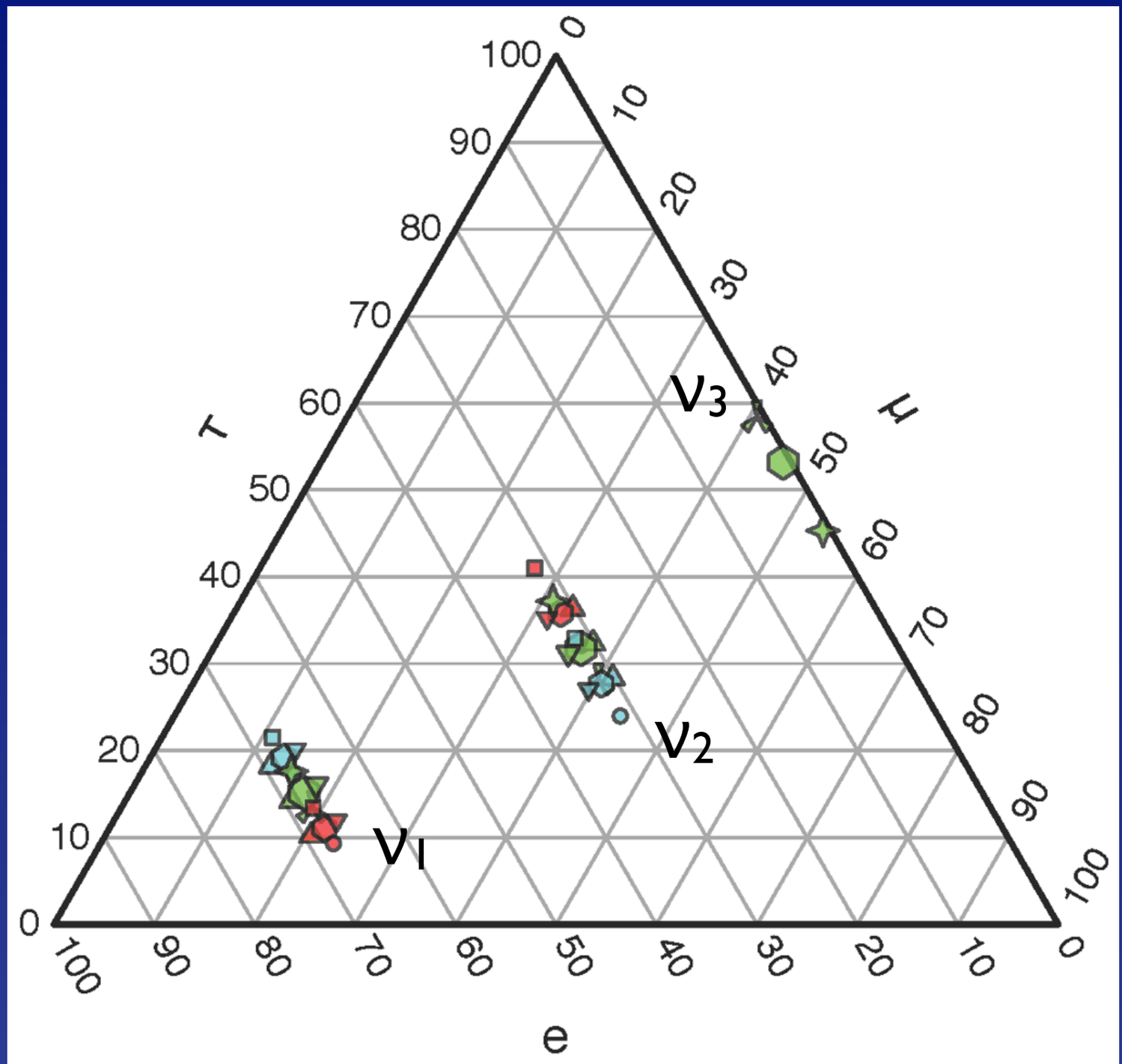
Running mass $m(m)$ … $m(U)$

Quark family patterns: *generations*

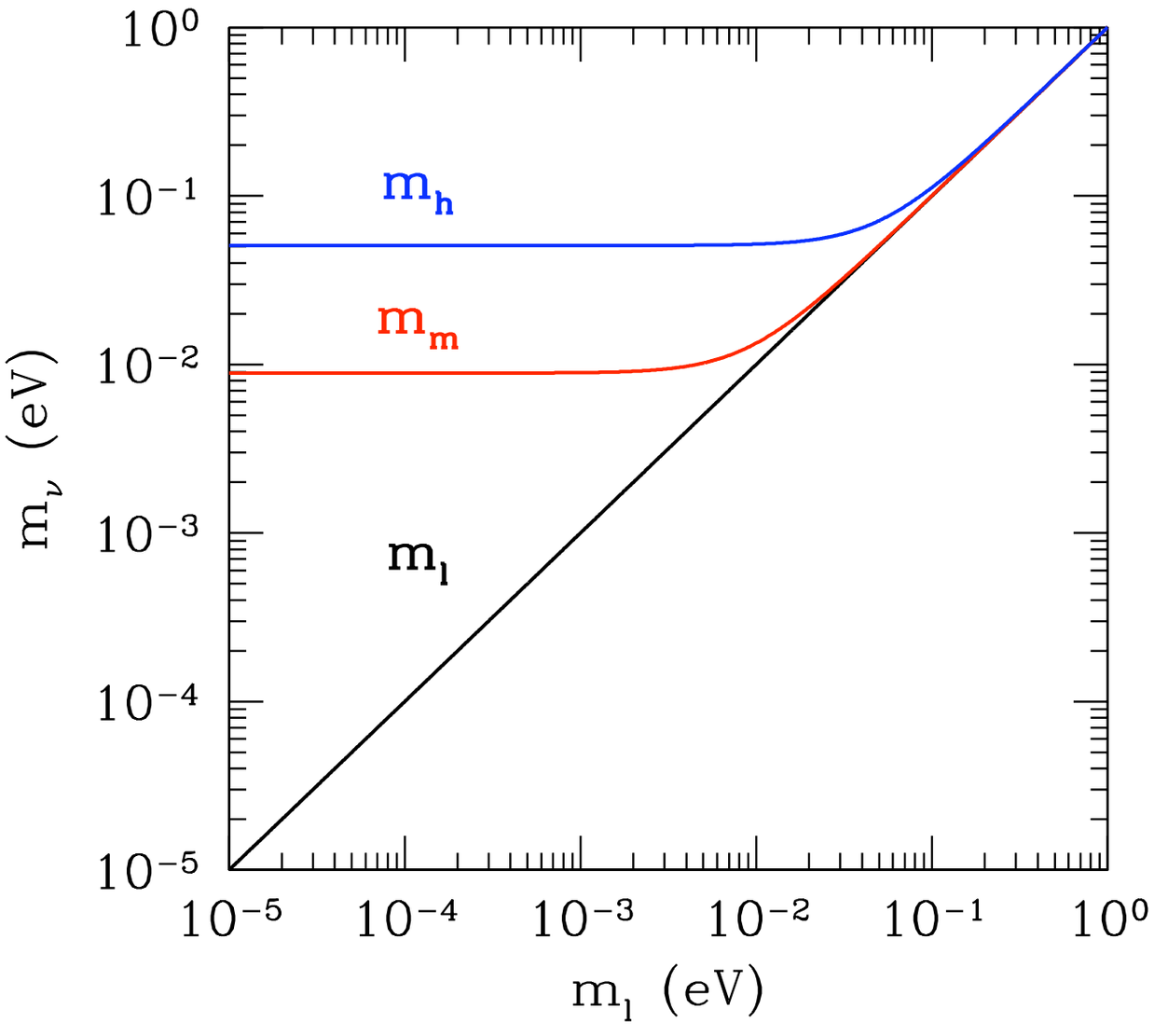


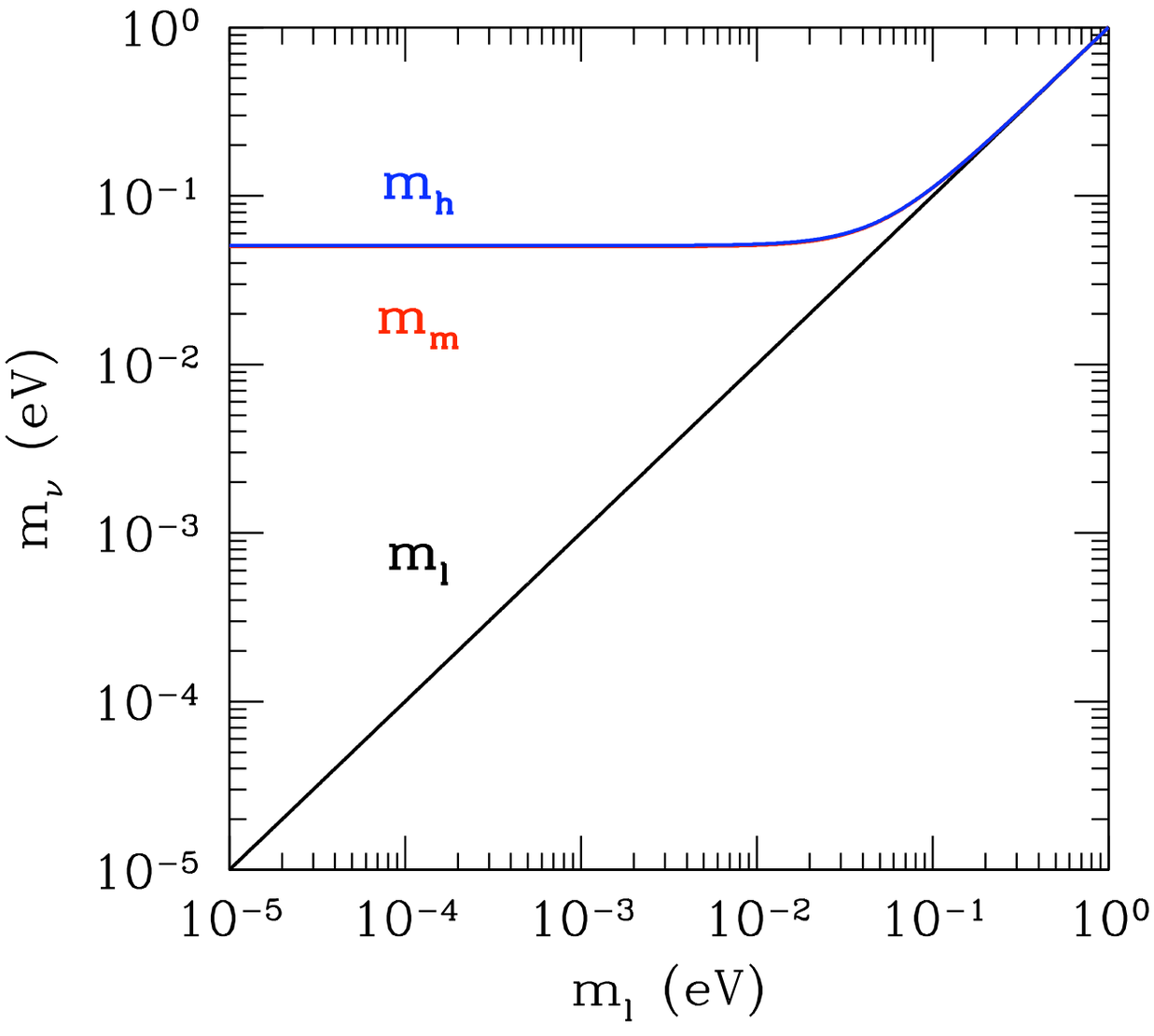
Veltman: Higgs boson knows something we don't know!

Neutrino family patterns

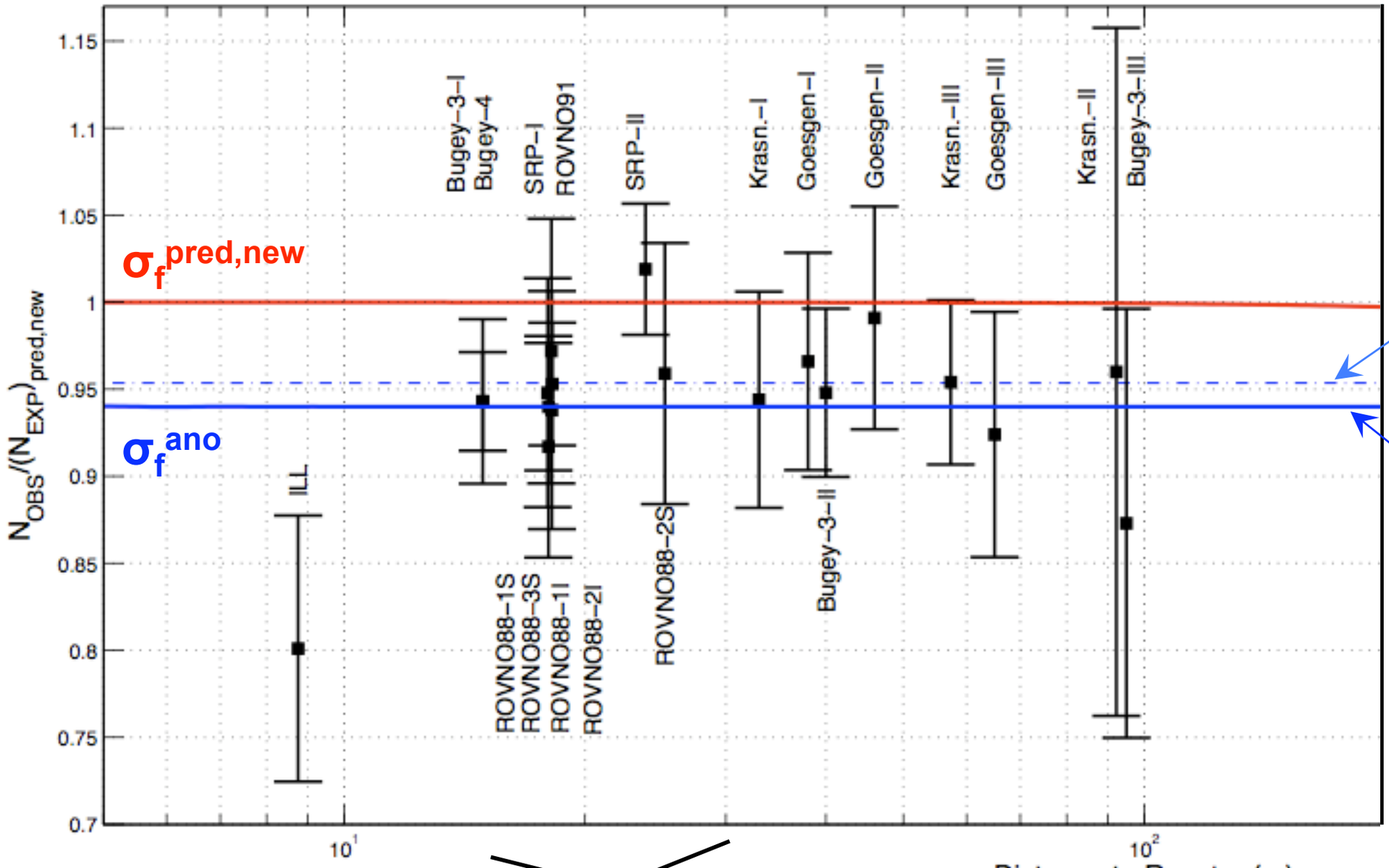


Neutrino Masses





Visual illustration of the anomaly



(naive weighted mean) $\sigma_f^{ano} = (0.95 \pm 0.01)\ \sigma_f^{pred,new}$

(correlated weighted mean) $\sigma_f^{ano} = (0.943 \pm 0.023)\ \sigma_f^{pred,new}$

mean value of measured quantities

from new flux conversion from ILL β-spectra

Will the fermion masses and mixings reveal symmetries or dynamics or principles?

What is CP violation trying to tell us?

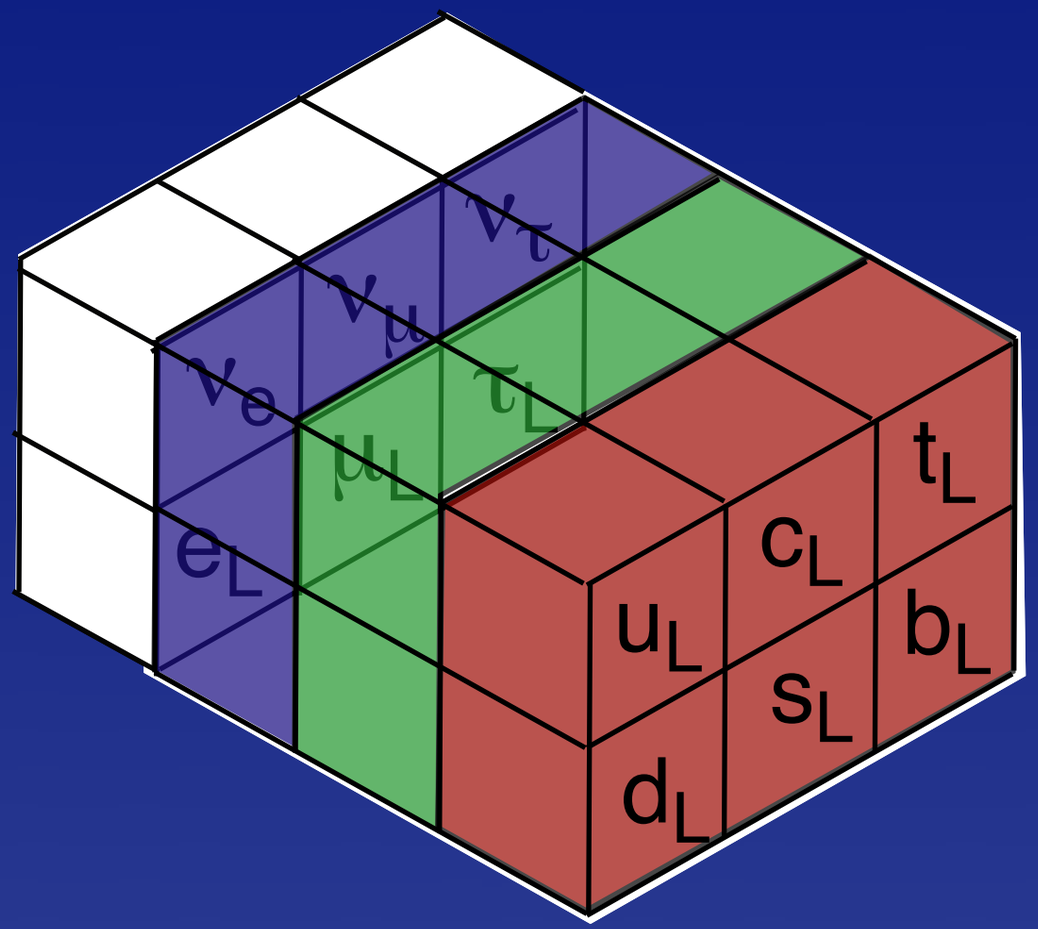
Some questions now seem to us the wrong questions:
Kepler's obsession – Why six planets in those orbits?

Landscape interpretation as environmental parameters

Might still hope to find equivalent of Kepler's Laws!

A Unified Theory?

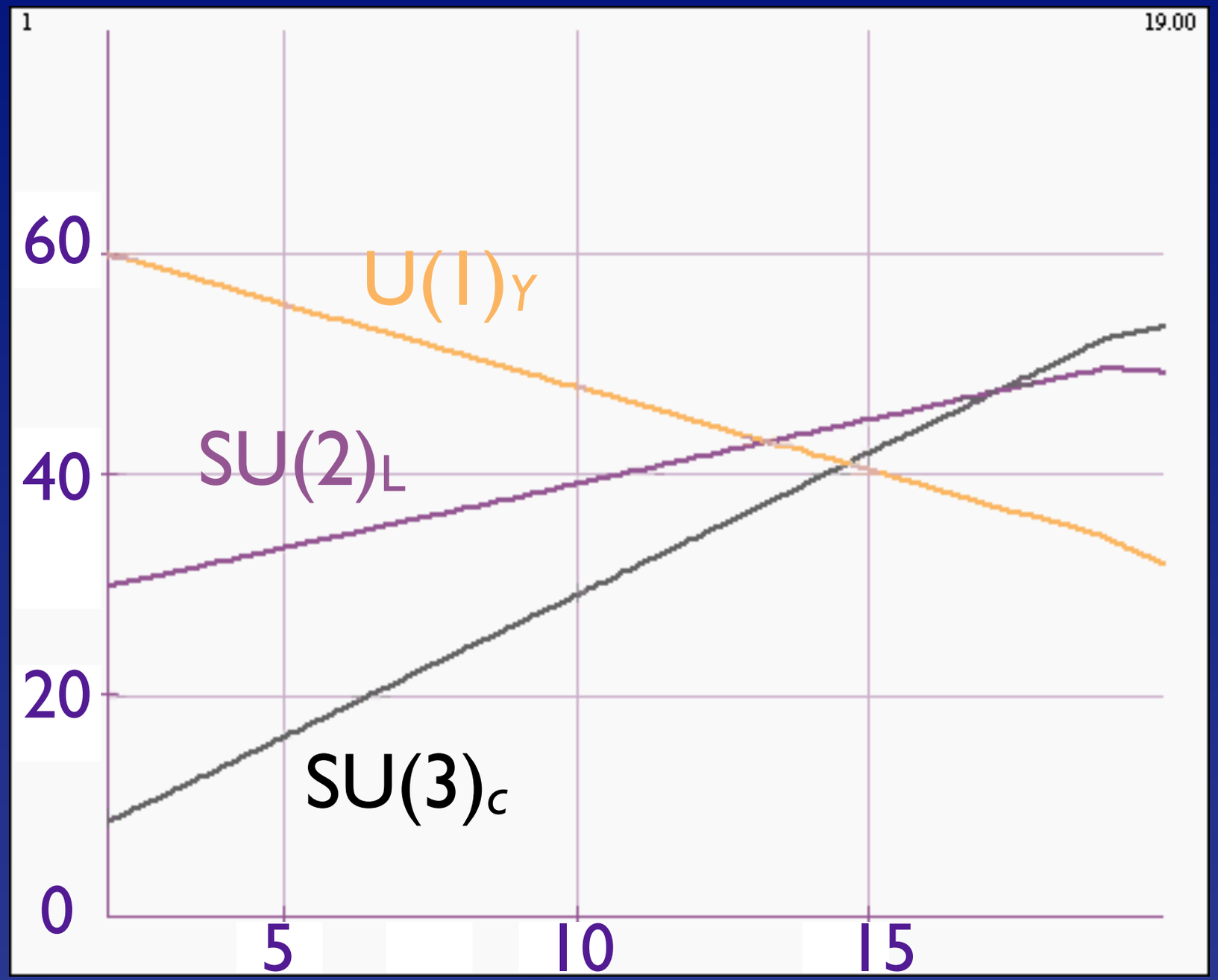
Why are atoms so remarkably neutral?



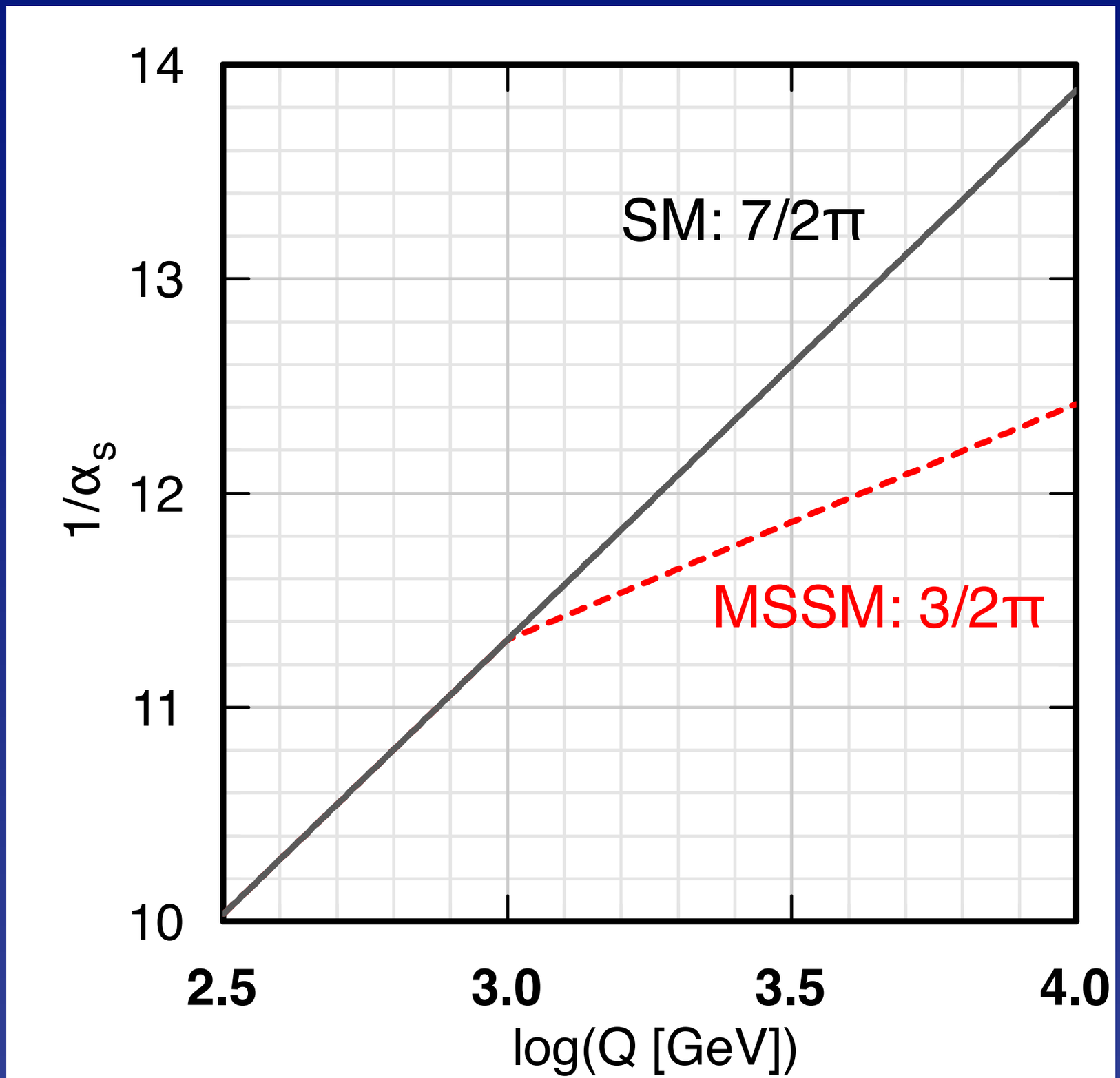
Coupling constant unification?

Extended quark–lepton families:
proton decay!

Unification of Forces?



Might LHC see the change in evolution?



An electroweak challenge:

Why is empty space so nearly massless?

Gravitational ep interaction $\approx 10^{-41}$ EM

But gravity is not always negligible …

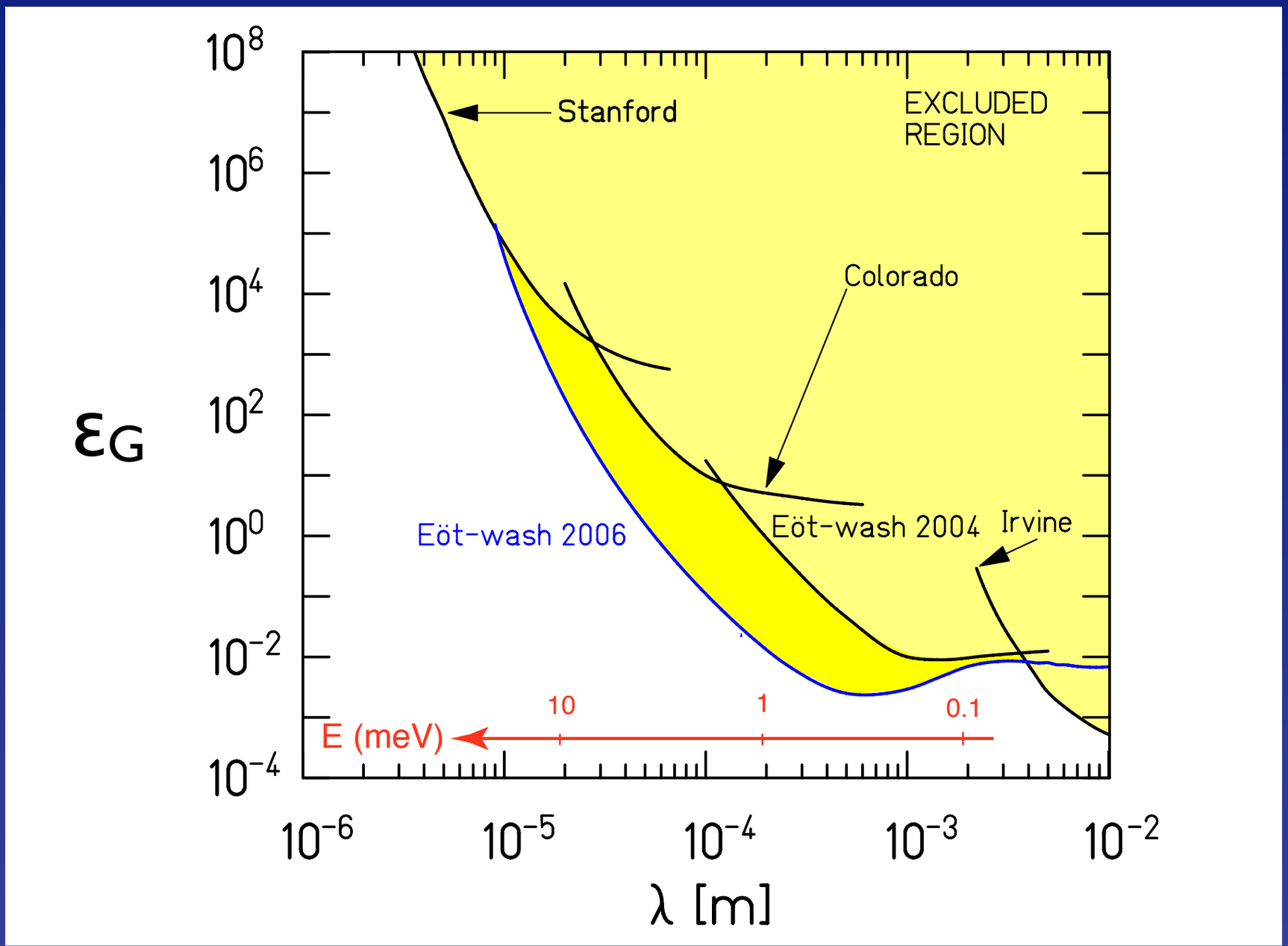
Higgs field contributes uniform vacuum energy density

$$\varrho_H \equiv \frac{M_H^2 v^2}{8} \geq 10^8 \text{ GeV}^4 \quad \approx 10^{28} \text{ g/liter}$$

$$\text{Critical density } \varrho_c \equiv \frac{3H_0^2}{8\pi G_{\text{Newton}}} \lesssim 10^{-26} \text{ g/liter}$$

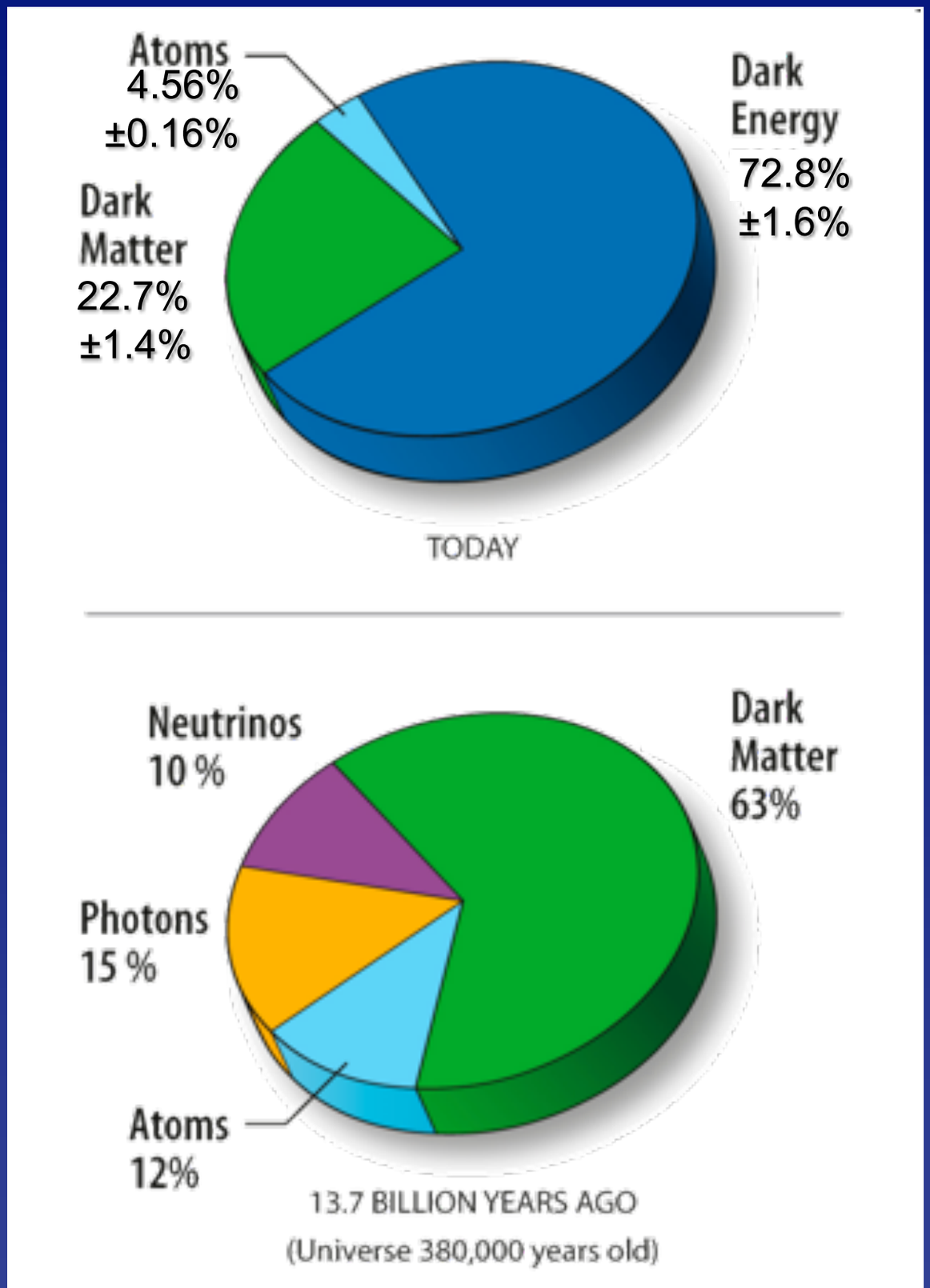
Gravity follows Newtonian force law down to ≲ 1 mm

$$V(r) = -\int dr_1 \int dr_2 \frac{G_{\text{Newton}}\rho(r_1)\rho(r_2)}{r_{12}}\left[1 + \varepsilon_{\text{G}}\exp(-r_{12}/\lambda_{\text{G}})\right]$$



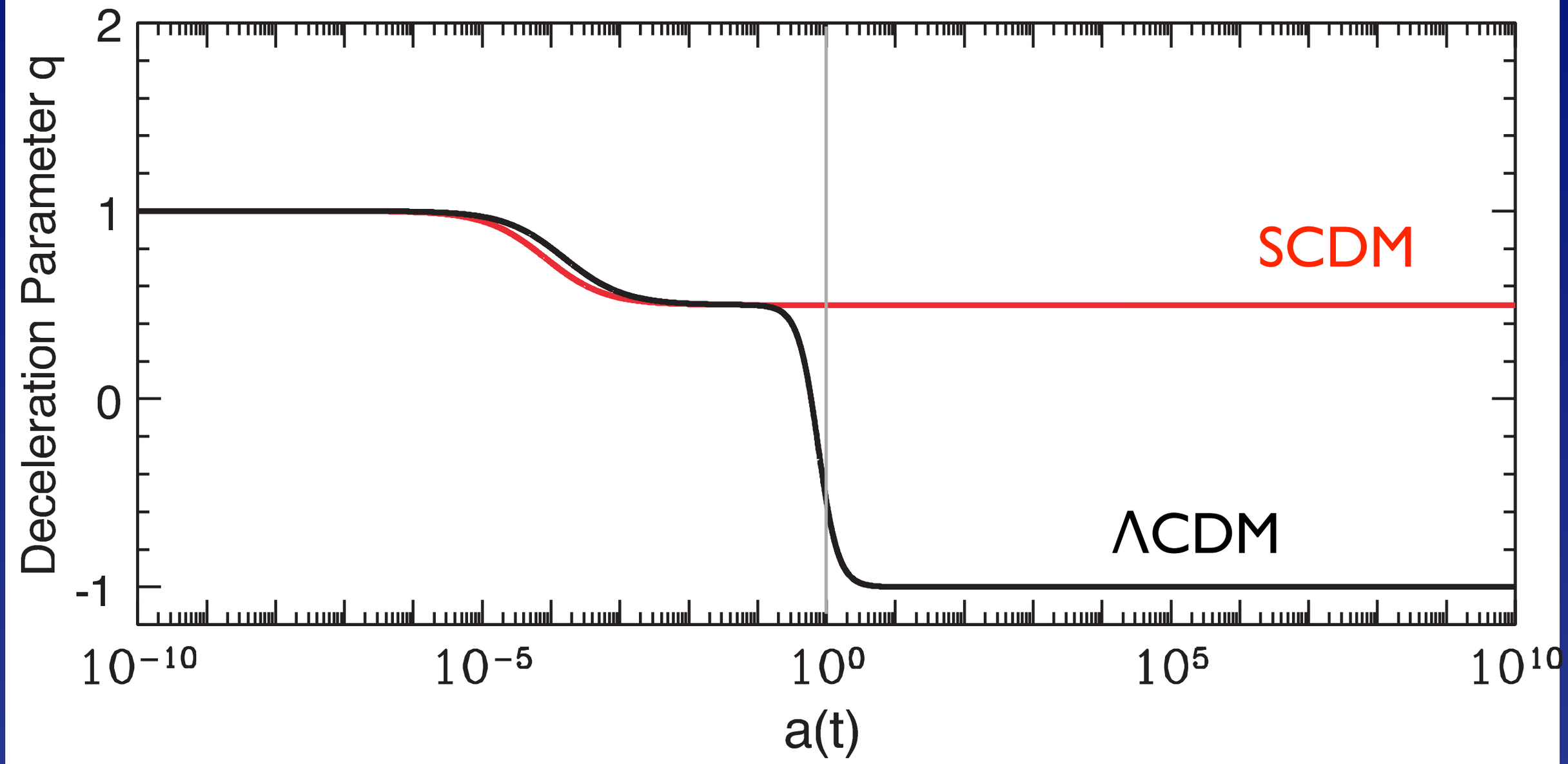
Composition Now and Then (WMAP)

$\Omega \approx 1$



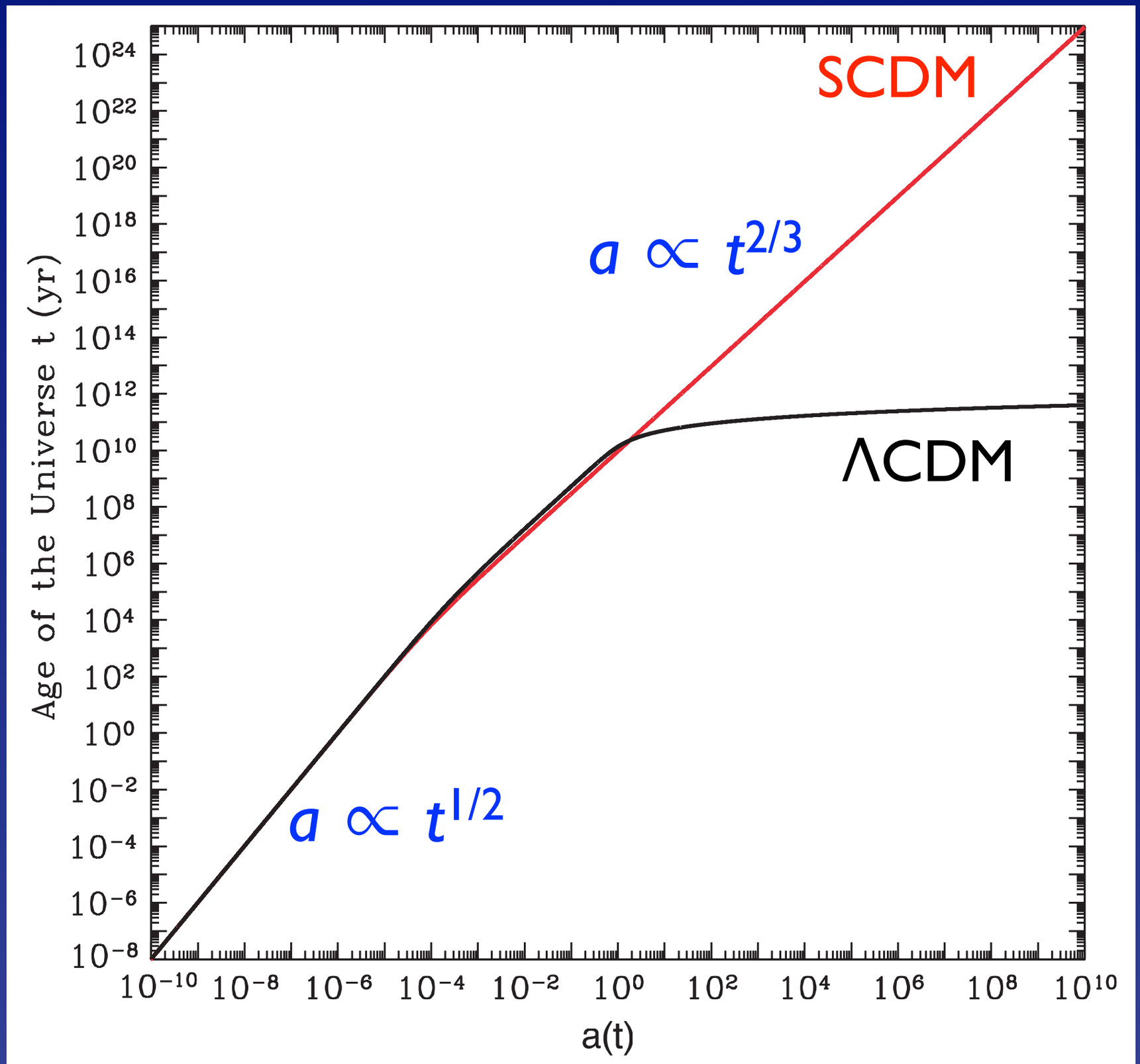
ΛCDM

Accelerating expansion has remarkable implications



$$q \equiv -\frac{1}{H^2}\frac{\ddot{R}}{R} = \frac{\Lambda}{3H^2} - \frac{4\pi G_{\rm N}}{3H^2}(\rho + 3p)$$

Accelerating expansion has remarkable implications



Perhaps not everything we know is true?

An invitation in my email:

Recently, ΛWDM (Warm Dark Matter) emerged impressively over ΛCDM (Cold Dark Matter) whose small-galactic-scale (and even larger scale) problems are ever-increasing …

ΛWDM solves naturally the problems of ΛCDM and agrees with the observations at small as well as large and cosmological scales.

?

Issues for the Future (Now!)

1. What is the agent of EWSB? Is there a Higgs boson? Might there be several?
2. Is the Higgs boson elementary or composite? How does it interact with itself? What triggers EWSB?
3. Does the Higgs boson give mass to fermions, or only to the weak bosons? What sets the masses and mixings of the quarks and leptons? *(How) is fermion mass related to the electroweak scale?*
4. Are there new flavor symmetries that give insights into fermion masses and mixings?
5. What stabilizes the Higgs-boson mass below 1 TeV?

Issues for the Future (Now!)

6. Do the different CC behaviors of LH, RH fermions reflect a fundamental asymmetry in nature's laws?
7. What will be the next symmetry we recognize? Are there additional heavy gauge bosons? Is nature supersymmetric? Is EW theory contained in a GUT?
8. Are all flavor-changing interactions governed by the standard-model Yukawa couplings? Does "minimal flavor violation" hold? If so, why?
9. Are there additional sequential quark & lepton generations? Or new exotic (vector-like) fermions?
10. What resolves the strong CP problem?

Issues for the Future (Now!)

11. What are the dark matters? Any flavor structure?
12. Is EWSB an emergent phenomenon connected with strong dynamics? How would that alter our conception of unified theories of the strong, weak, and electromagnetic interactions?
13. Is EWSB related to gravity through extra spacetime dimensions?
14. What resolves the vacuum energy problem?
15. (When we understand the origin of EWSB), what lessons does EWSB hold for unified theories? … for inflation? … for dark energy?

Issues for the Future (Now!)

16. What explains the baryon asymmetry of the universe? Are there new (CC) CP-violating phases?
17. Are there new flavor-preserving phases? What would observation, or more stringent limits, on electric-dipole moments imply for BSM theories?
18. (How) are quark-flavor dynamics and lepton-flavor dynamics related (beyond the gauge interactions)?
19. At what scale are the neutrino masses set? Do they speak to the TeV scale, unification scale, Planck scale, …?

20. How are we prisoners of conventional thinking?